Supernovae : Laboratories for Fundamental ν Physics

Manibrata Sen
UC Berkeley & Northwestern University

Network for Neutrinos, Nuclear Astrophysics and Symmetries (N3AS)

Fermilab
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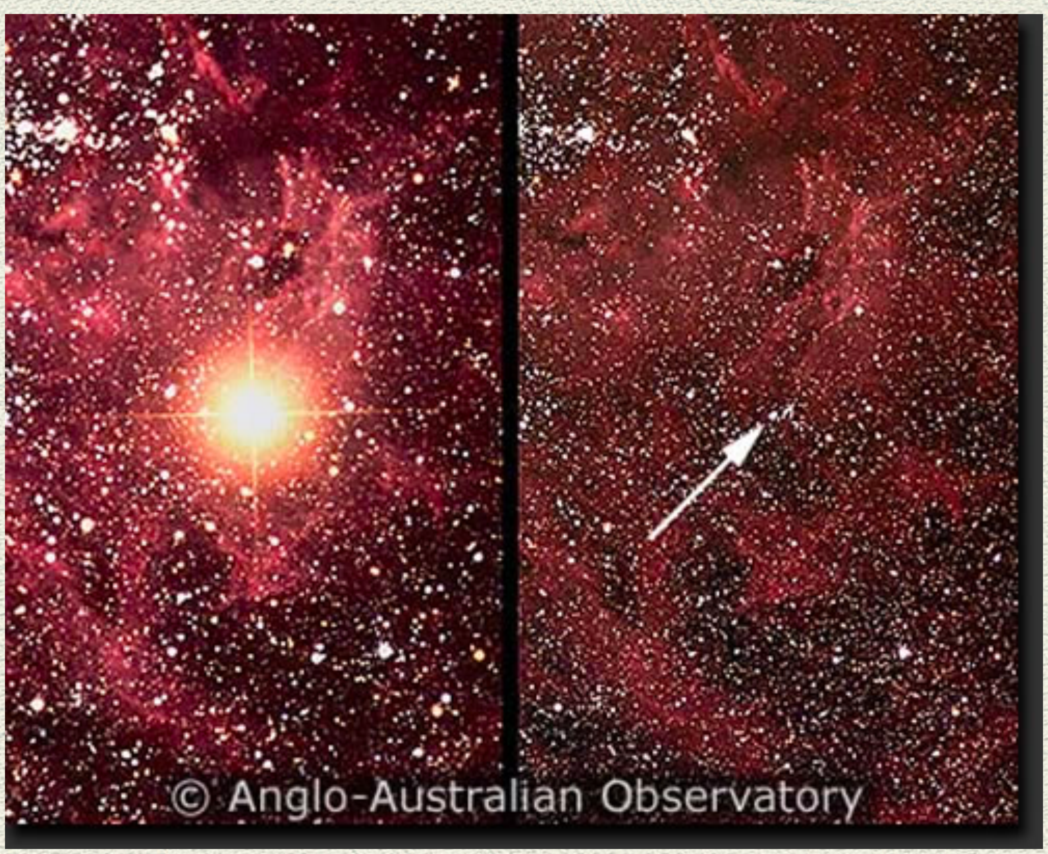
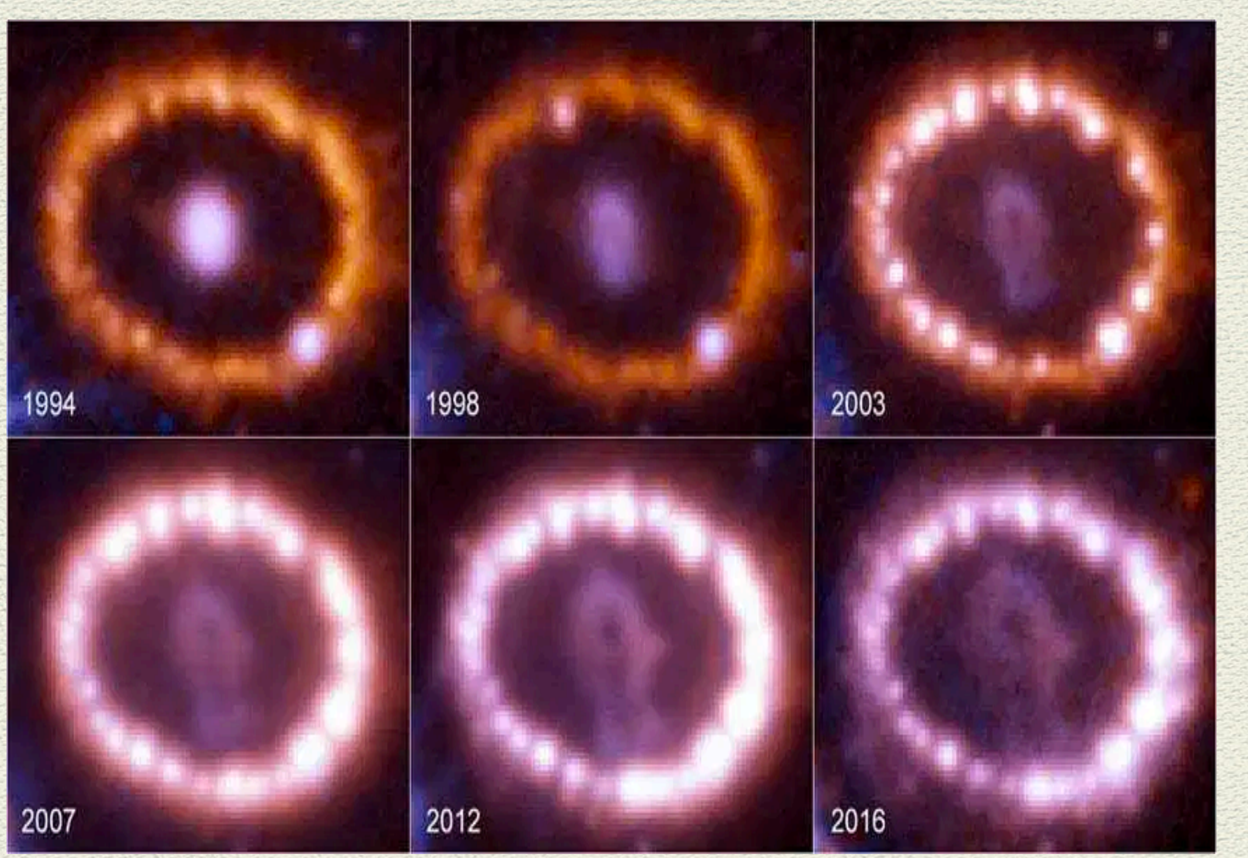
SN 1987A: the poster boy of supernovae

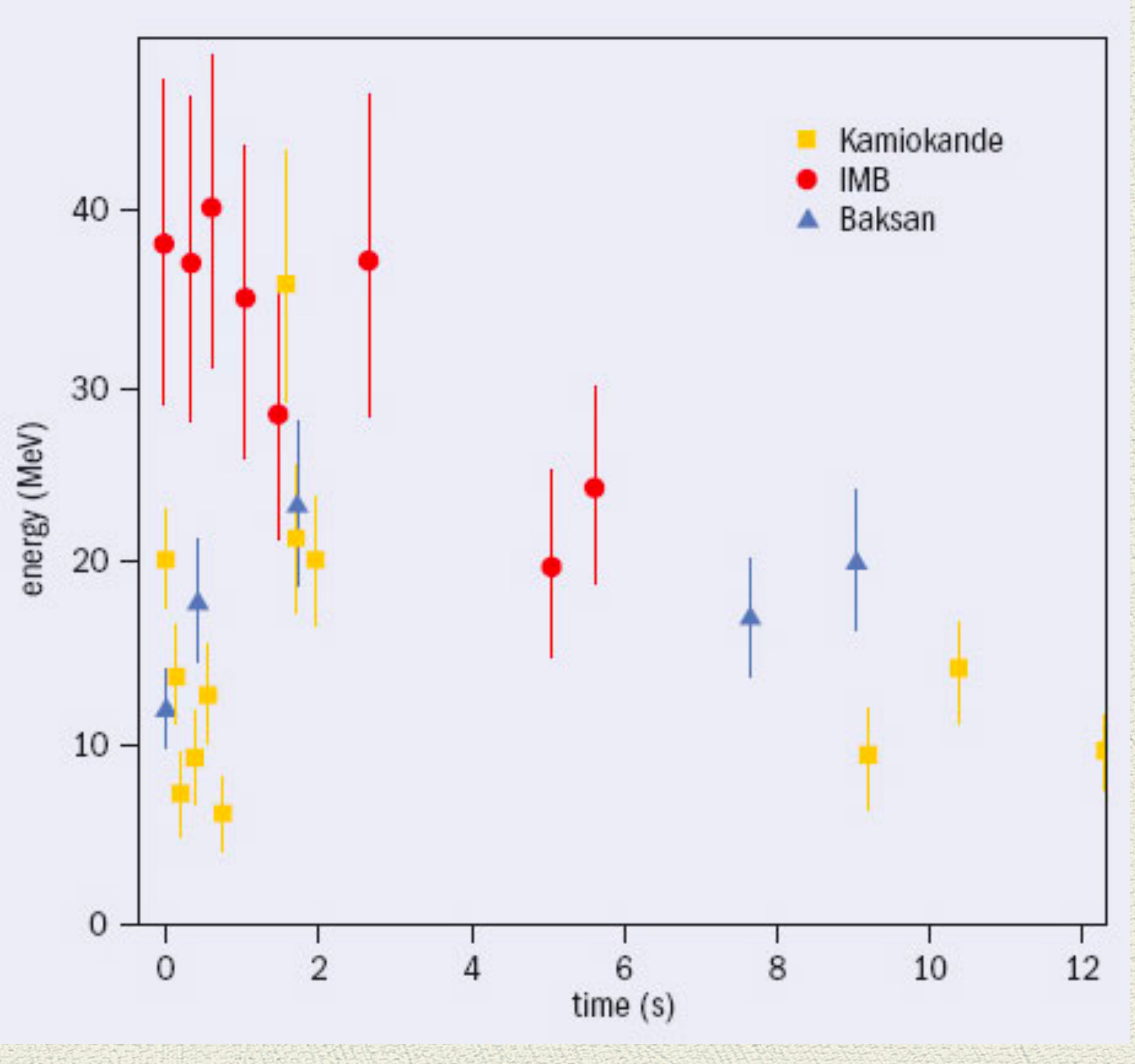
Feb 23, 1987





- Took place168k years ago
- In the Large Magellanic Cloud, 50 kpc away. $18 M_\odot$ star.

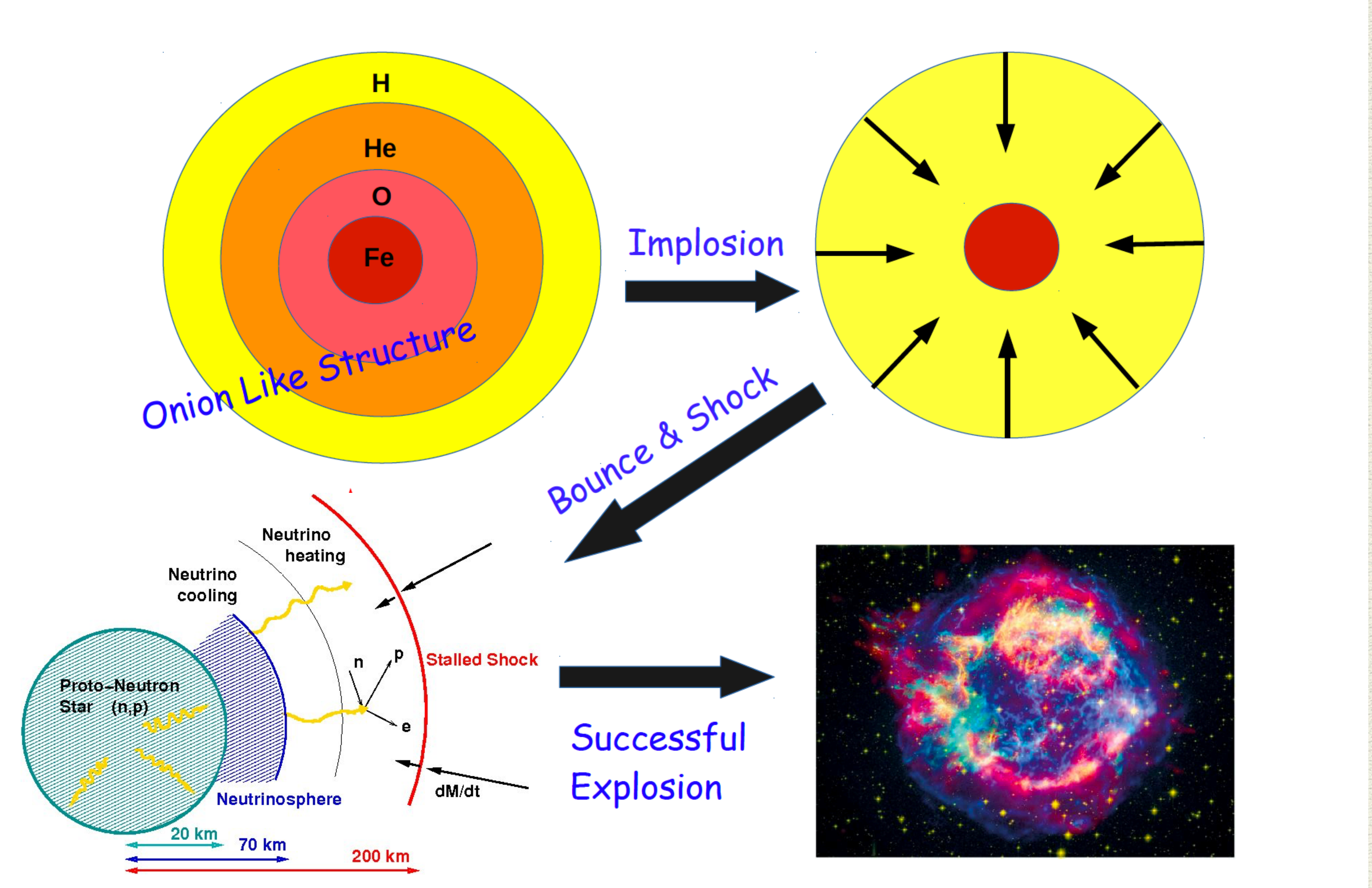
“Many” neutrinos were observed



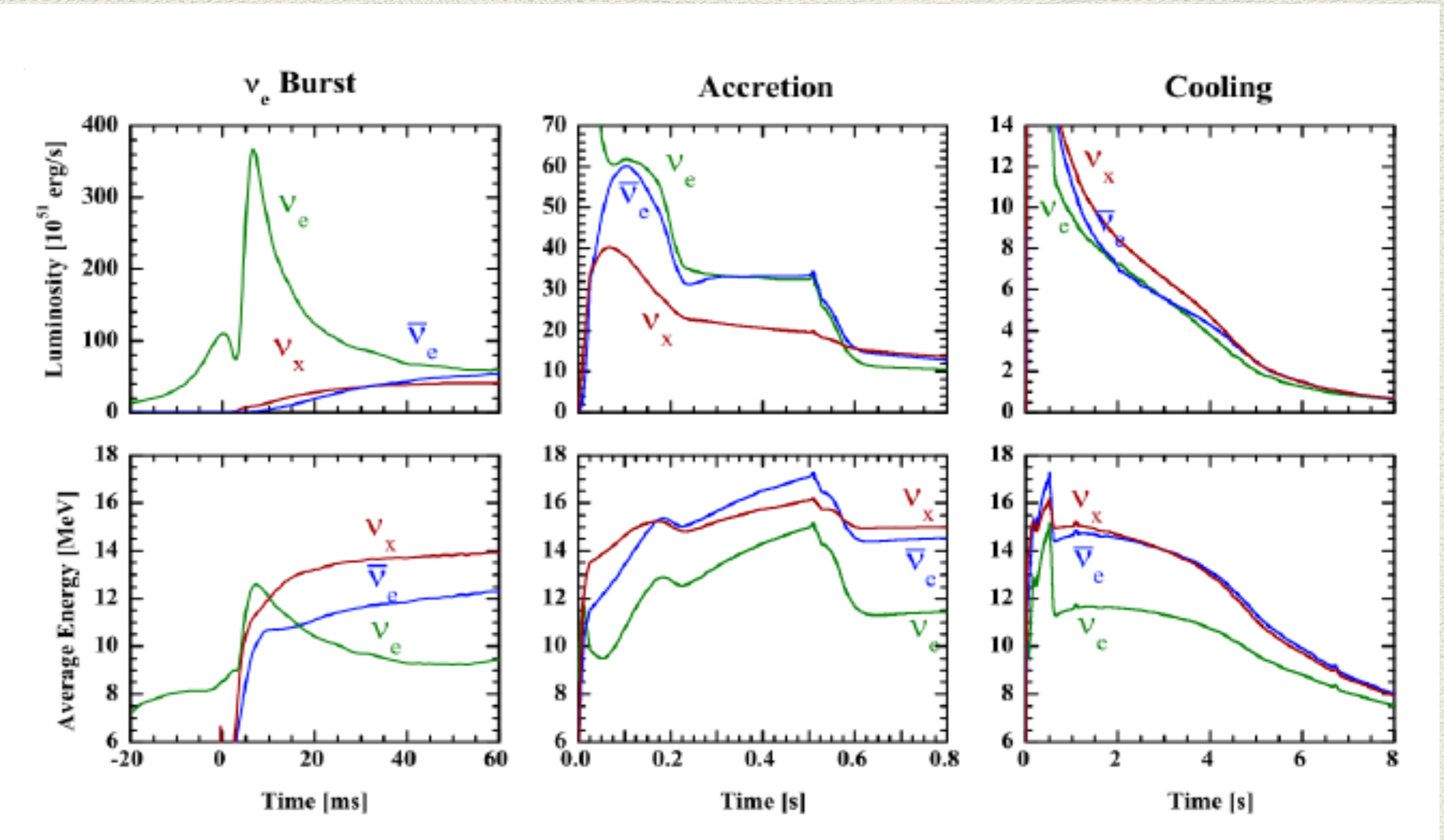
- O(30) events in total.
- One of the first examples of multi-messenger astronomy.
- Neutrinos before photons.
- Not enough statistics, still a coherent picture can be formed!

A coherent story…

CCSN Odyssey



Phases of neutrino emission

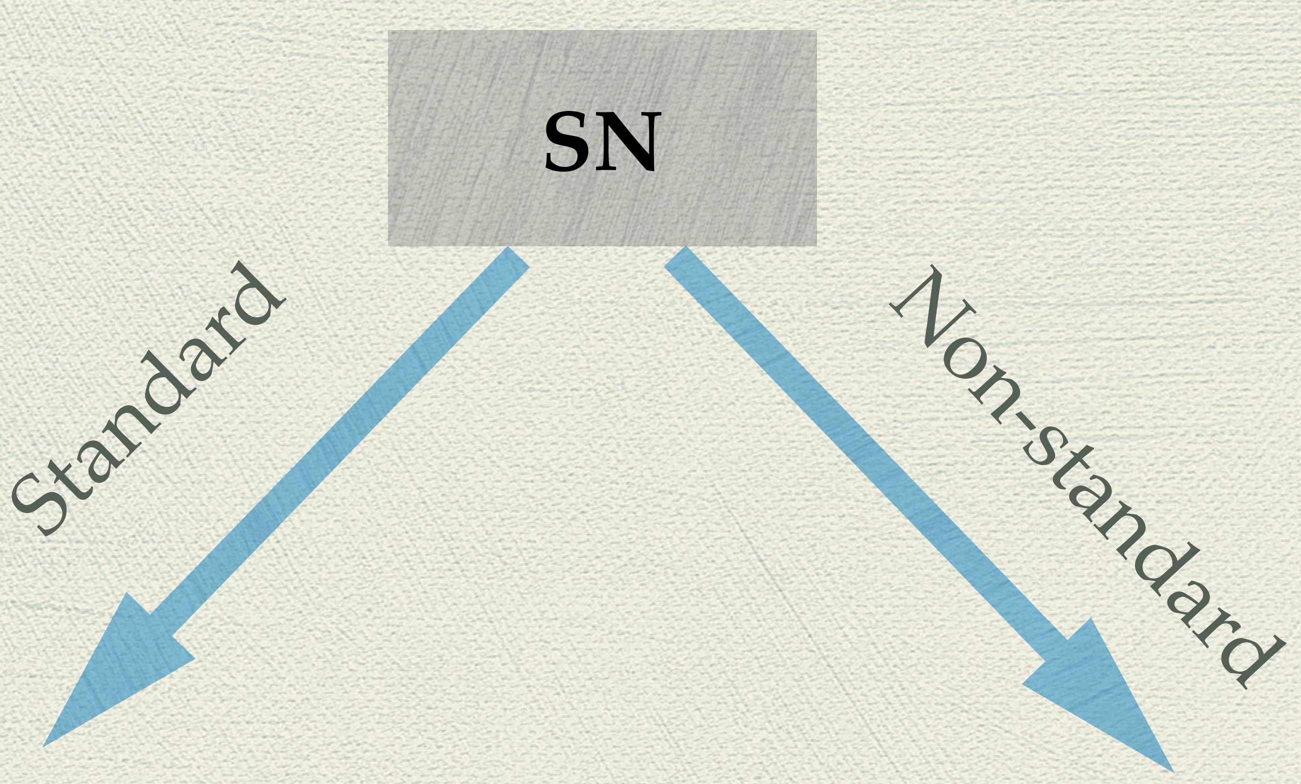


Late time νs
???

- $\sim 10^{58}$ neutrinos emitted.
- 99% energy of the star carried away.

1D simulation of a 27 solar mass star by the Garching group

What sort of a laboratory is the SN?



- νs probe stellar interiors.
- Relevant information about supernova dynamics, shockwave propagation, turbulence.
- Physics of dense neutrino streams. Can lead to “collective oscillations”!

- Non-standard neutrino properties: decay, self-interactions, magnetic moment, Dirac-Majorana nature, etc.
- New particles.
- Any crazy stuff that theorists can think about.

How to model neutrinos from a SN?

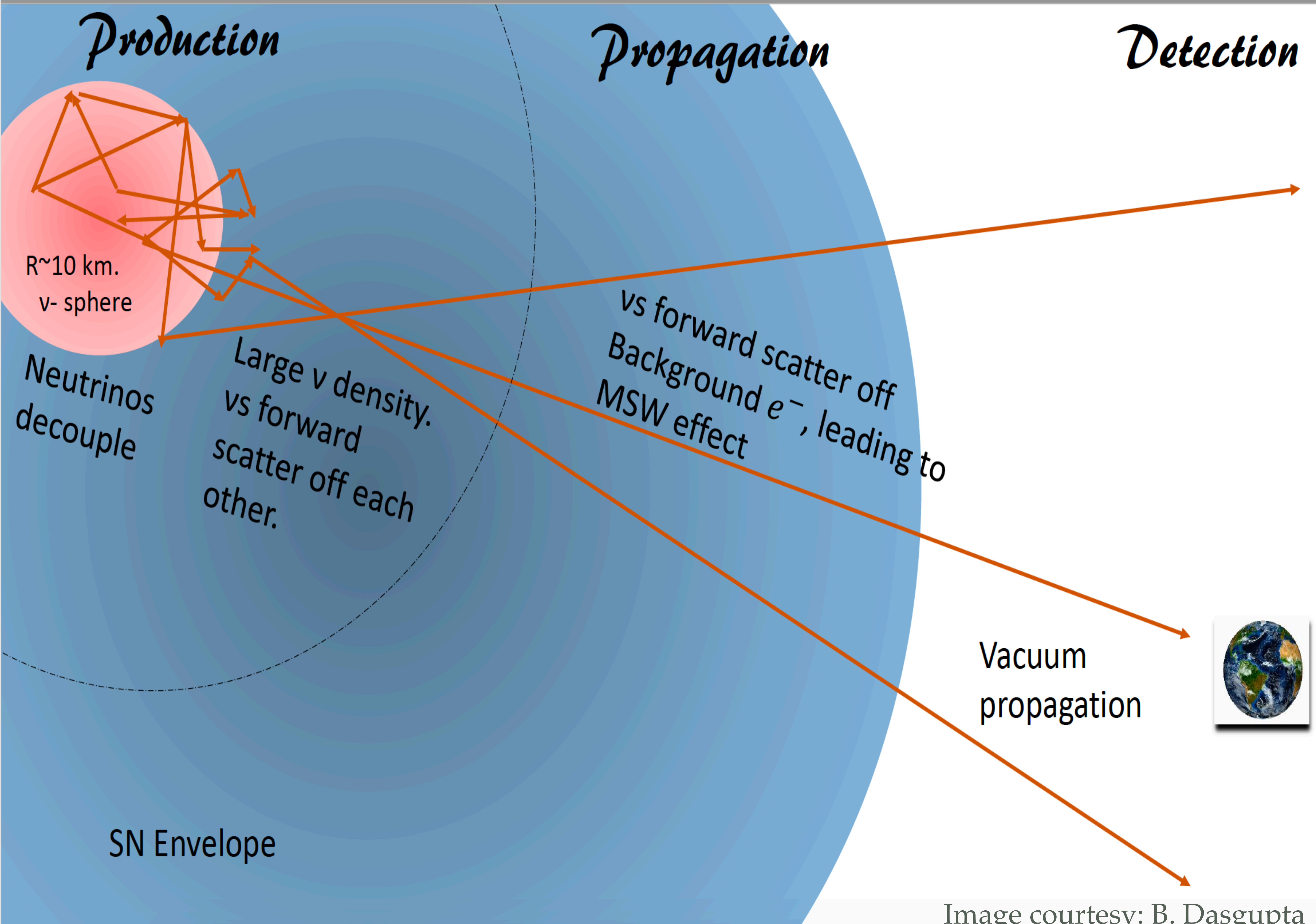
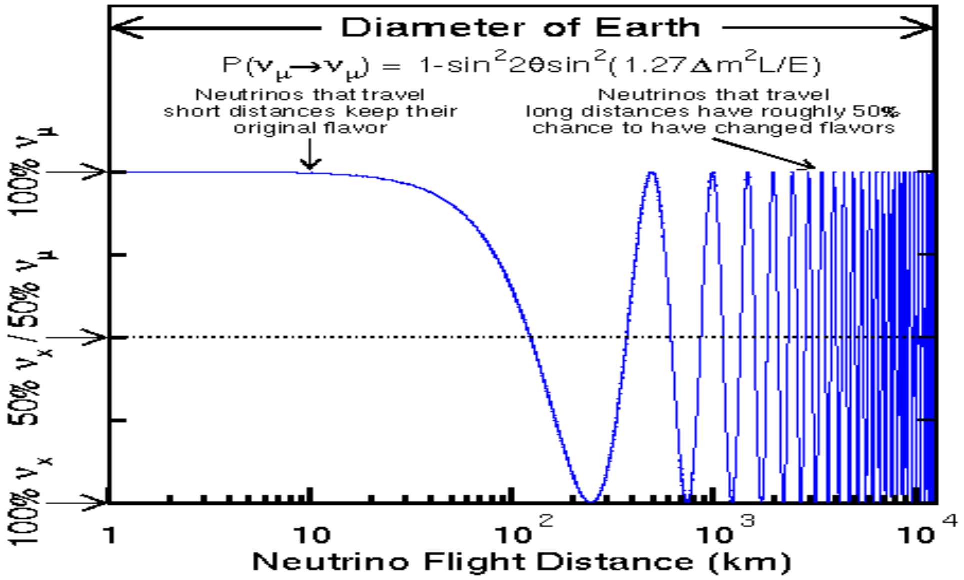


Image courtesy: B. Dasgupta

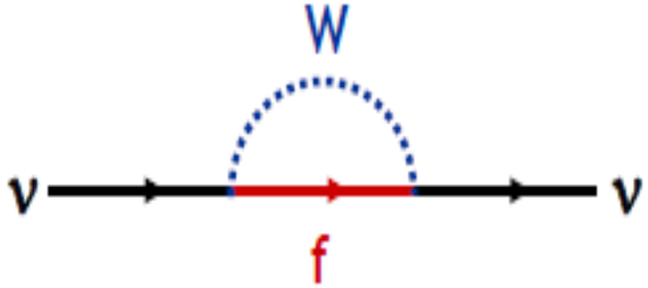
A brief detour into ν oscillations: 2 flavors

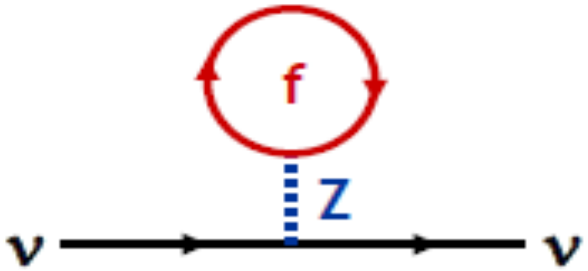
In vacuum

$$i d_t \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \frac{\Delta m^2}{2\mathrm{E}} \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$



While traveling through matter





Wolfenstein (PRD 1977)

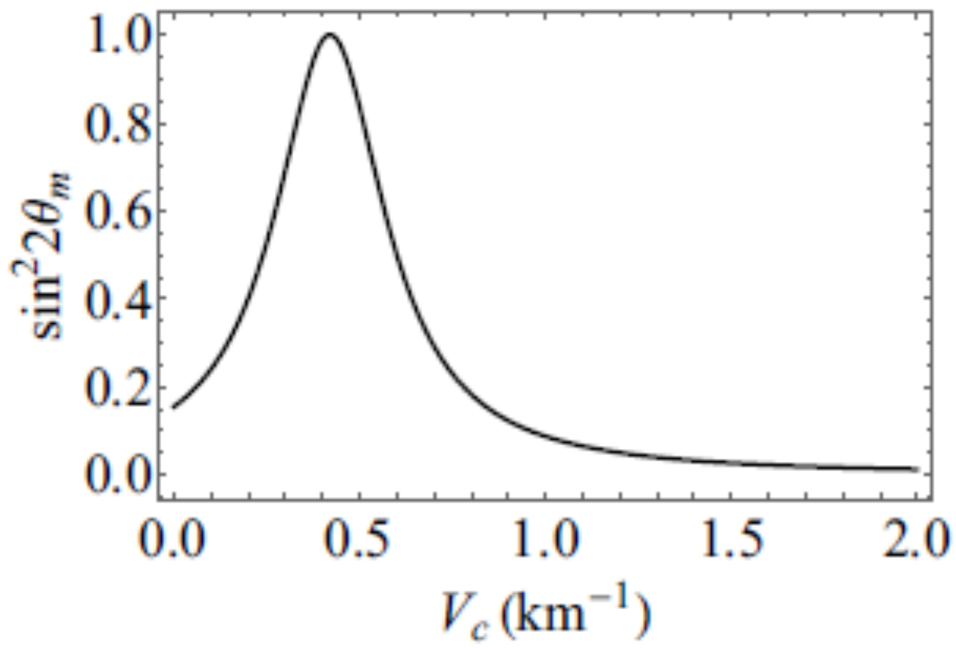
Mikheyev and Smirnov (Sov.J.Nuc.Phys. 1985)

$$i d_t \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \frac{\Delta m^2}{2\mathrm{E}} \cos 2\theta + \sqrt{2}\, G_F\, (n_e - n_n/2) & \frac{\Delta m^2}{2\mathrm{E}} \sin 2\theta \\ \frac{\Delta m^2}{2\mathrm{E}} \sin 2\theta & -\frac{\Delta m^2}{2\mathrm{E}} \cos 2\theta - \sqrt{2}\, G_F\, n_n/2 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

MSW flavor conversions

- Effective mixing angle in matter:

$$\sin 2\theta_M = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\sqrt{\left(\frac{\Delta m^2}{2E}\cos 2\theta - V(r)\right)^2 + \left(\frac{\Delta m^2}{2E}\sin 2\theta\right)^2}}$$



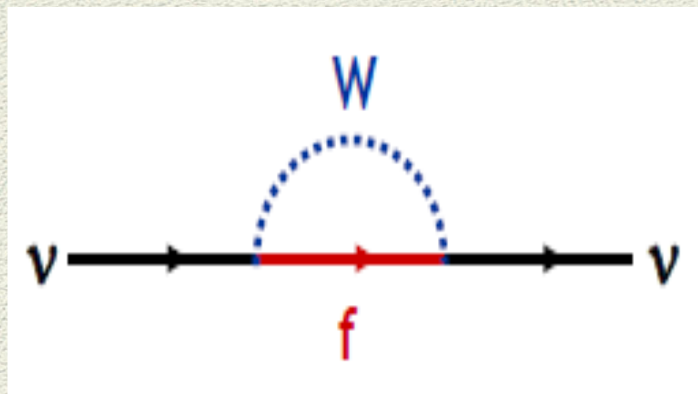
- Enhanced flavor conversions when

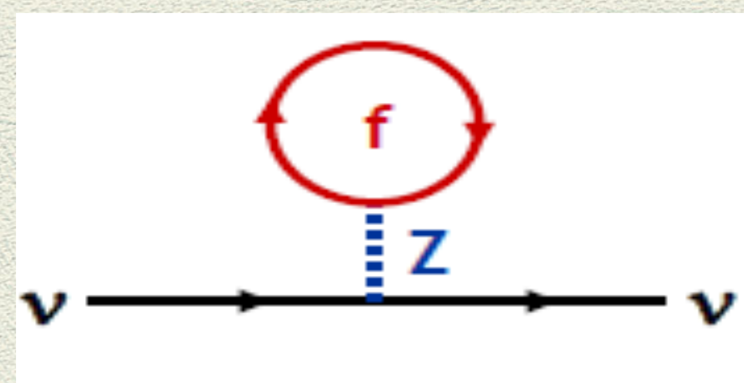
$$\frac{\Delta m^2}{2E}\cos 2\theta = V(r)$$

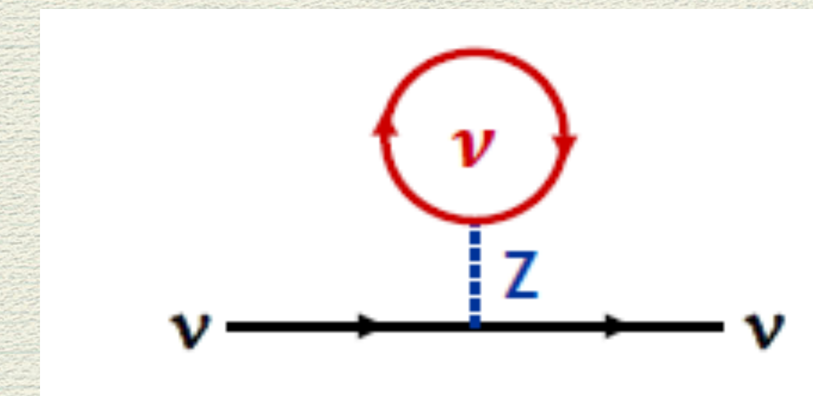
- Rate of oscillations $\propto \omega = \frac{\Delta m^2}{2E}$
- Solution of the solar neutrino problem.

Wolfenstein (PRD 1977)
Mikheyev and Smirnov (Sov.J.Nuc.Phys. 1985)

How is the story different for a SN?







•Neutrino density so high that they feel additional potential. Only lab where neutrino self-interactions become important.

•This makes flavor evolution a complicated non-linear problem.

$$H = \frac{M^2}{2E} + \sqrt{2}G_{\mathrm{F}} \begin{pmatrix} N_e - \frac{N_n}{2} & 0 \\ 0 & -\frac{N_n}{2} \end{pmatrix} + \sqrt{2}G_{\mathrm{F}} \begin{pmatrix} N_{\nu_e} & N_{\langle \nu_e | \nu_\mu \rangle} \\ N_{\langle \nu_\mu | \nu_e \rangle} & N_{\nu_\mu} \end{pmatrix}$$

Mass term in flavor basis: causes vacuum oscillations

Wolfenstein's weak potential, causes MSW "resonant" conversion together with vacuum

Flavor-off-diagonal potential, caused by flavor oscillations. (J.Pantaleone, PLB 287:128,1992)

Raffelt, Seattle 2015

The matrix of densities: (1+3+3)d

$$\varrho = \begin{bmatrix} \langle \nu_e | \nu_e \rangle & \langle \nu_e | \nu_x \rangle \\ \langle \nu_x | \nu_e \rangle & \langle \nu_x | \nu_x \rangle \end{bmatrix}$$

EoM: $$d_t \varrho_p(r, p, t) = -i[H_p, \varrho_p] + C[\varrho_p]$$

$$H_p = \omega_p + \lambda + \mu \int d\Gamma' (1 - v_p \cdot v_{p'}) \varrho_{p'}$$

ω_p: $\frac{\mathrm{M}^2}{2\mathrm{E_p}}$

λ: Matter (MSW) term $\propto \sqrt{2} G_F n_e$

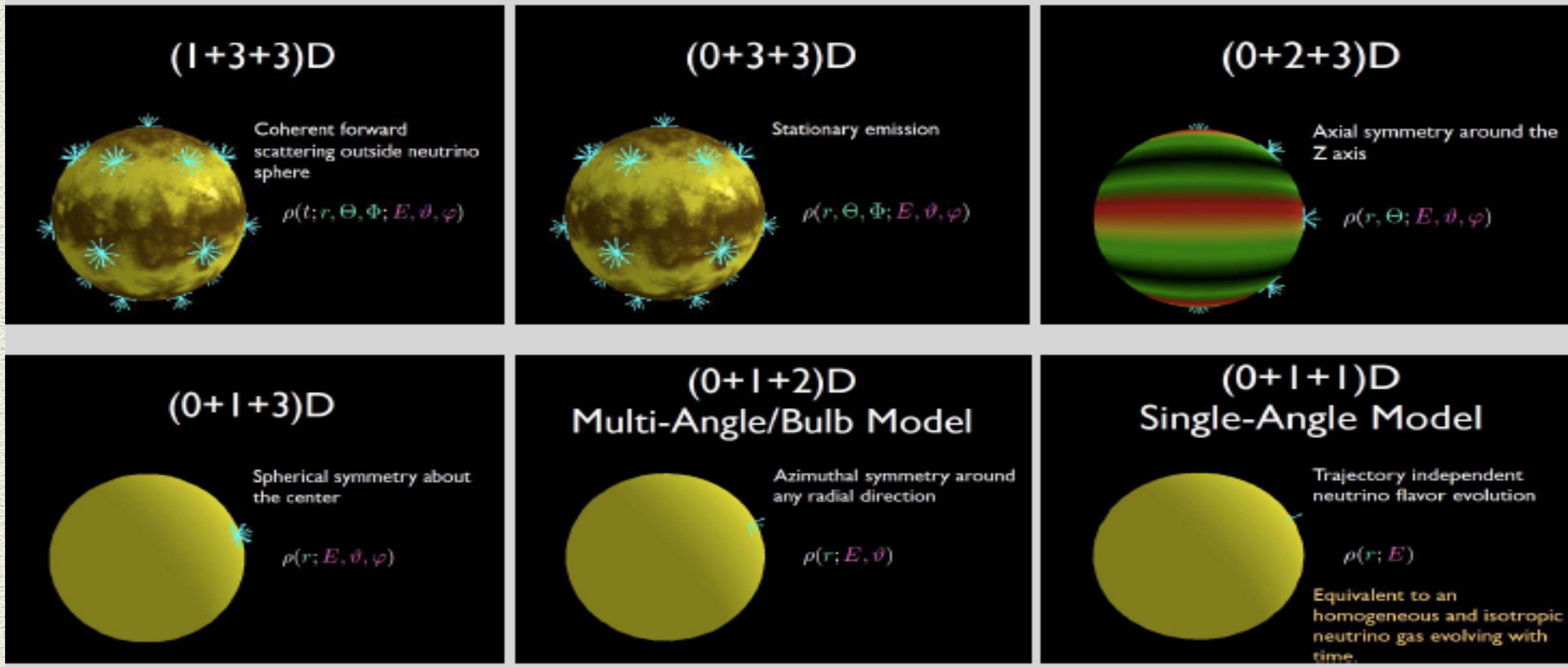
μ: $\nu - \nu$ interaction term $\propto n_\nu$

Kim, Kim and Sze (PRD 1988)

$$\mu \sim \lambda \gg \omega$$

Wolfenstein (PRD1978,1979)
Mikheyev and Smirnov (SJNP1985)
Pantaleone (PRD 1992)
Duan, Fuller, Carlson and Qian (PRD 2006,2007)
Hannestad, Raffelt, Sigland Wong (2006)

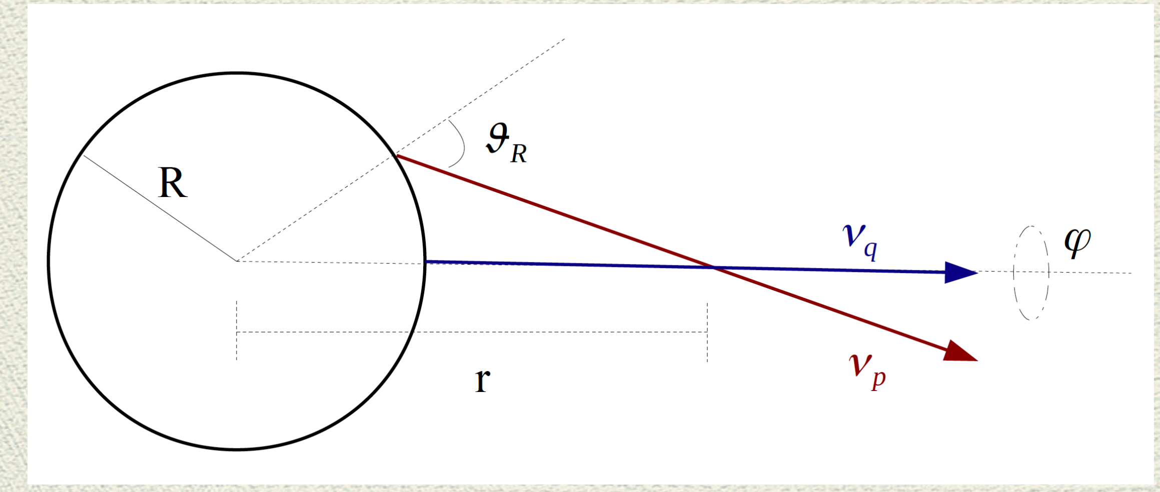
Neutrino transport, in its entirety



slides from H. Duan

Duan & Shalgar, PLB 2015
Mirizzi, Mangano & Saviano, PRD 2015

Simplest version: single energy and angle



$$\nu: \qquad d_t \varrho_p = -i[\omega_p + \mu(\varrho_p - \overline{\varrho_p}), \varrho_p]$$

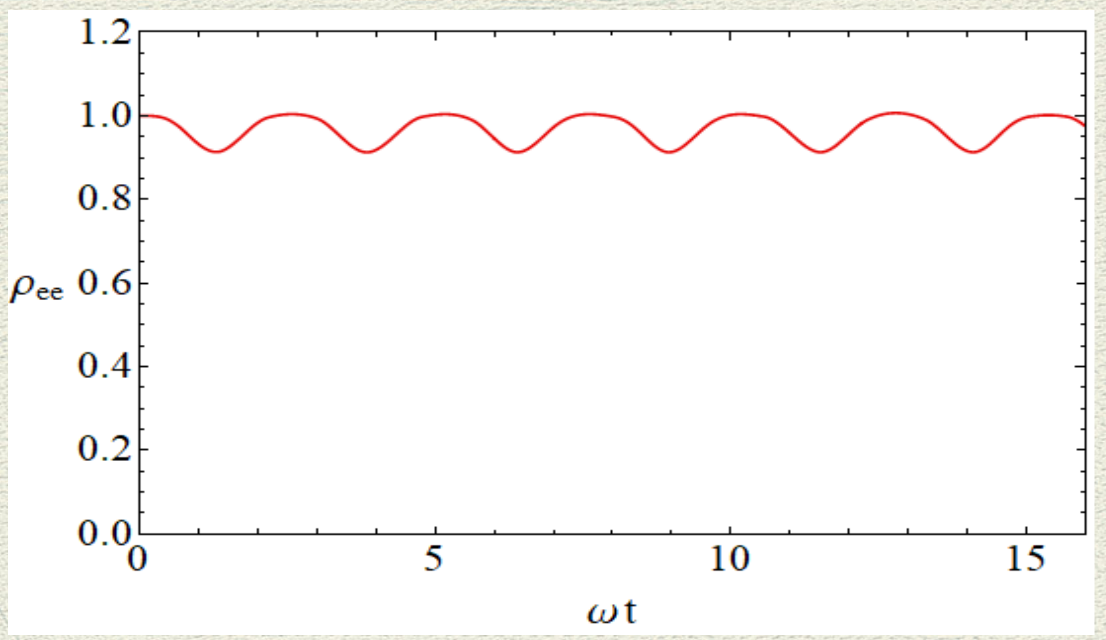
$$\bar{\nu}: \qquad d_t \overline{\varrho_p} = -i[-\omega_p + \mu(\varrho_p - \overline{\varrho_p}), \overline{\varrho_p}]$$

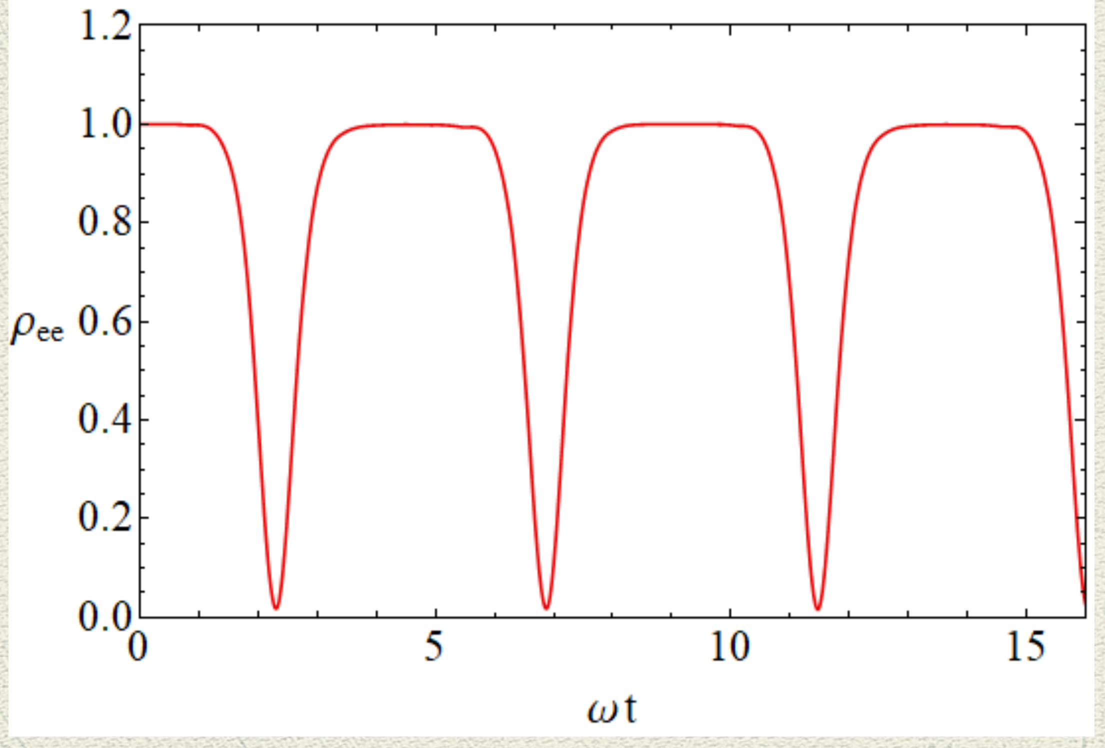
The simplest of systems demonstrate rich physics of an interacting neutrino gas!

Duan, Fuller, Carlson and Qian (PRL 2006)

Collective oscillations: effect of non-linearity

- If $\mu \propto n_\nu \gg \omega$, oscillations are synchronized.
- As n_ν decreases, bipolar oscillations $\nu_e\bar{\nu}_e \leftrightarrow \nu_\mu\bar{\nu}_\mu$ take place.
- Can lead to complete flavor conversions.
- Rate of oscillations $\sqrt{\omega\mu} \sim 10^3\omega$ near the nu-sphere.

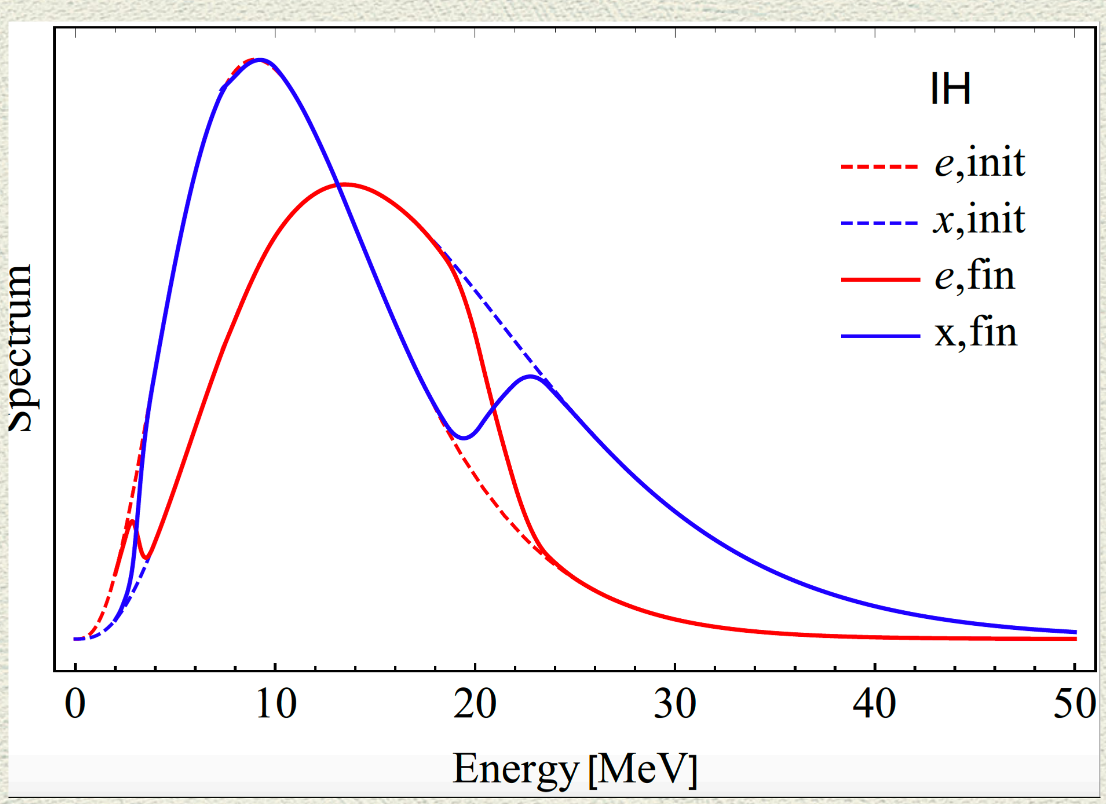


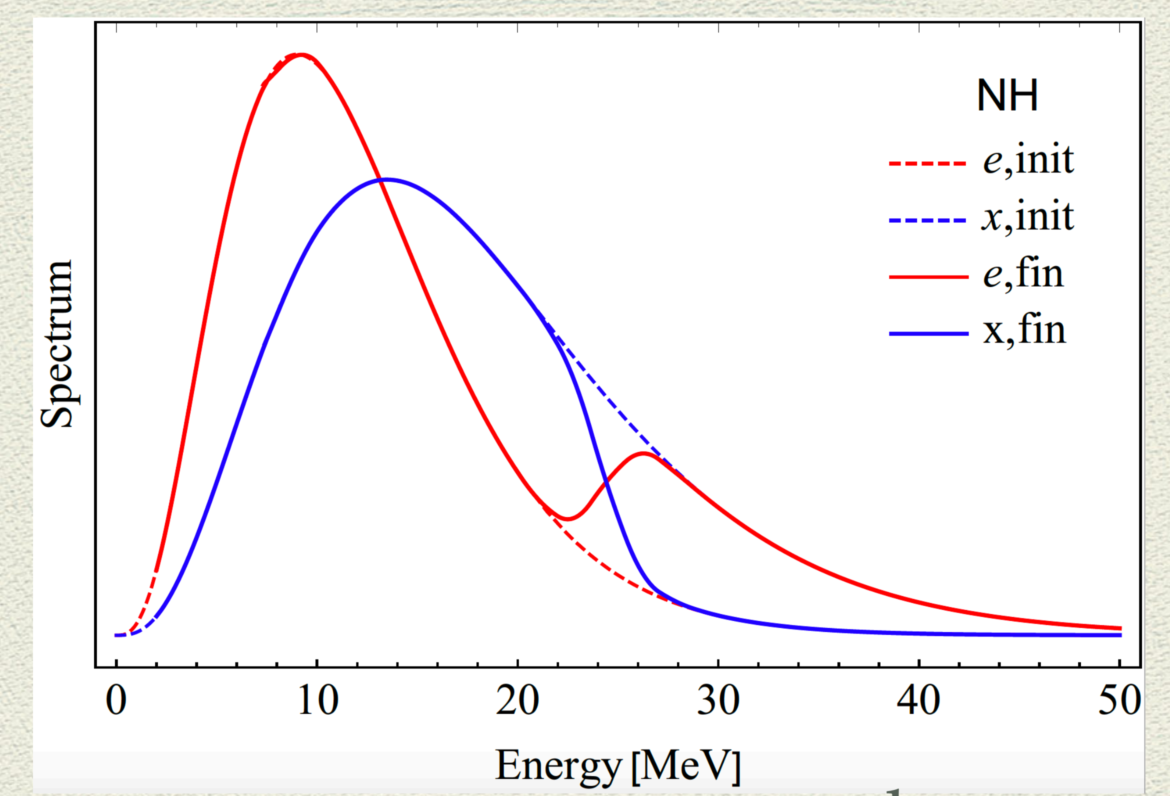


Duan, Fuller, Carlson and Qian (PRD 2006,2007; PRL 2006)

Hannestad, Raffelt, Sigl and Wong (PRD 2006)

Spectral swaps: formation of splits





e= electron

x=muon or tau

Bipolar oscillations lead to large 'spectral swaps': smoking gun signal of collective oscillations. Can be detected!

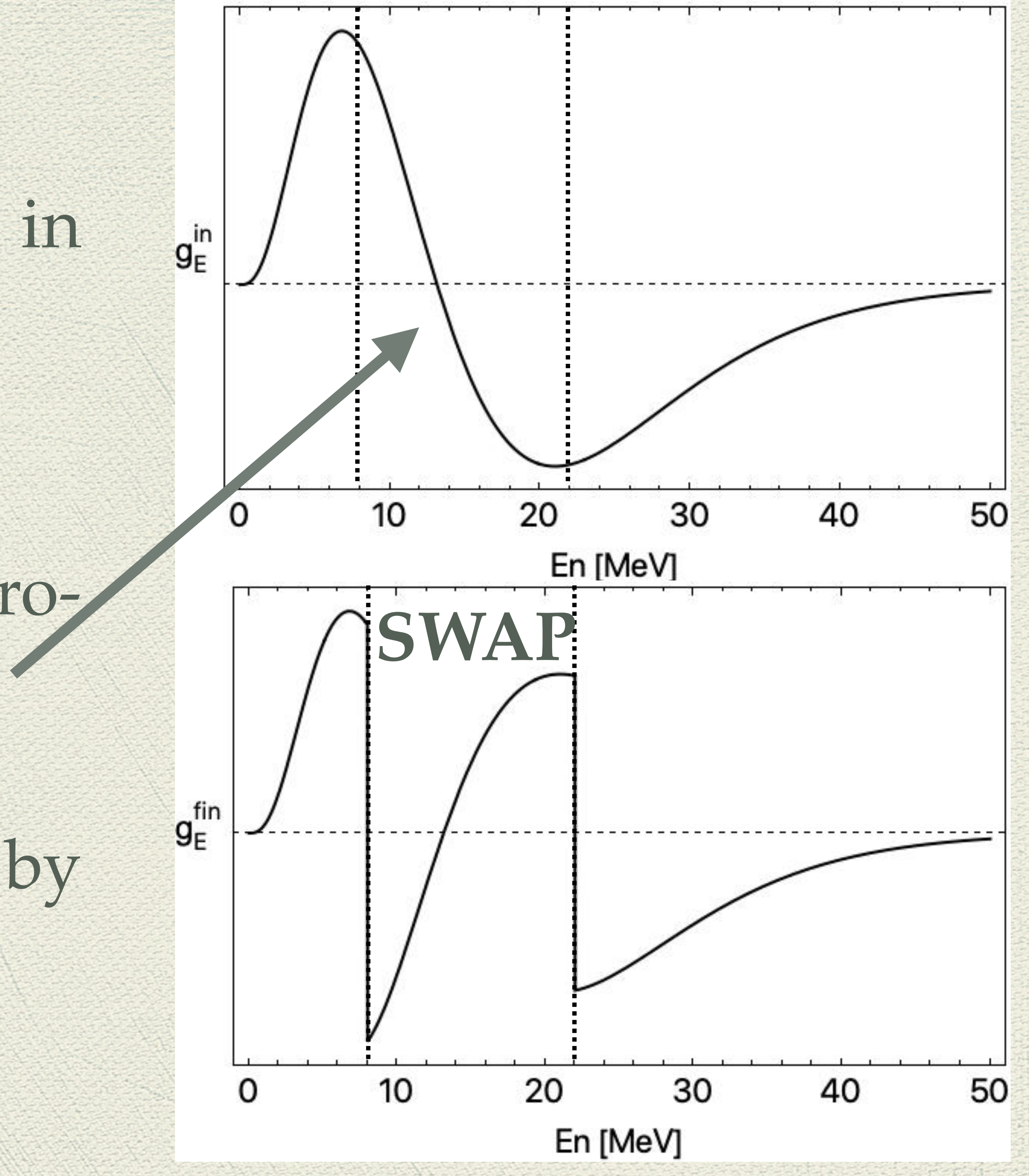
Duan, Fuller, Carlson and Qian (PRL 2006)

Dasgupta, Dighe, Mirizzi and Raffelt (PRD 2008)

Friedland (PRL 2010)

Spectral swaps: formation of splits

- Extremely difficult to explain analytically.
- Empirical explanation in terms of $g(E) = f_e(E) - f_x(E)$
- Swaps develop around zero-crossings of g(E).
- Width of swap governed by lepton # conservation.



Dasgupta, Dighe, Raffelt and Smirnov (PRL 2009)

How are these self-induced oscillations relevant?

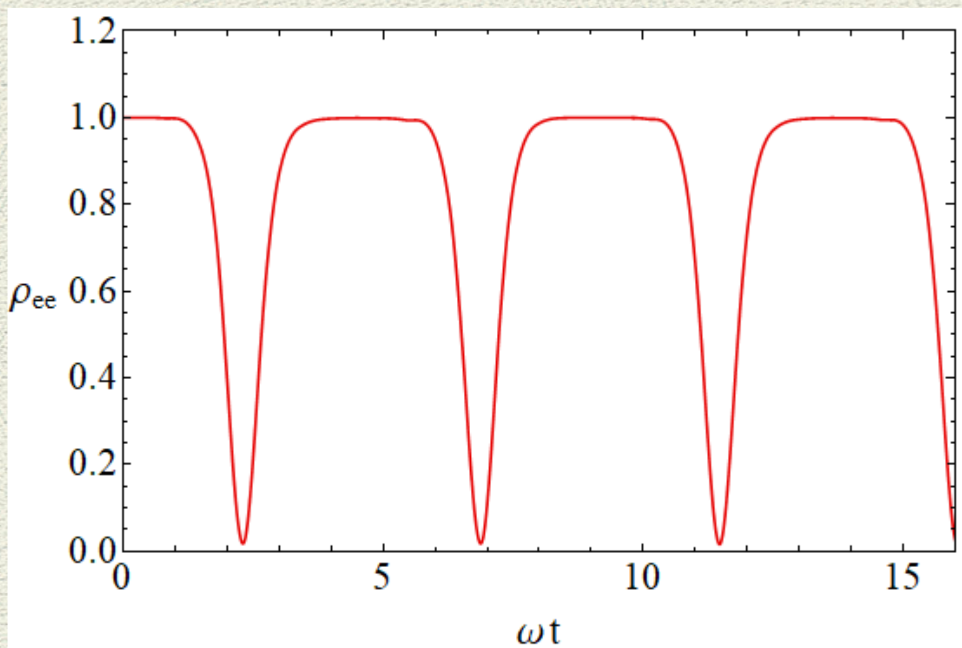
- Provides a method of converting ν_μs to ν_es deep inside a star.

- $\langle E_{\nu_\mu} \rangle > \langle E_{\nu_e} \rangle$. This leads to net heating of matter outflow, since the ν_e can deposit energy. Can be crucial for reheating the stalled shockwave.

- Such conversions are not suppressed by tiny mixing angles.

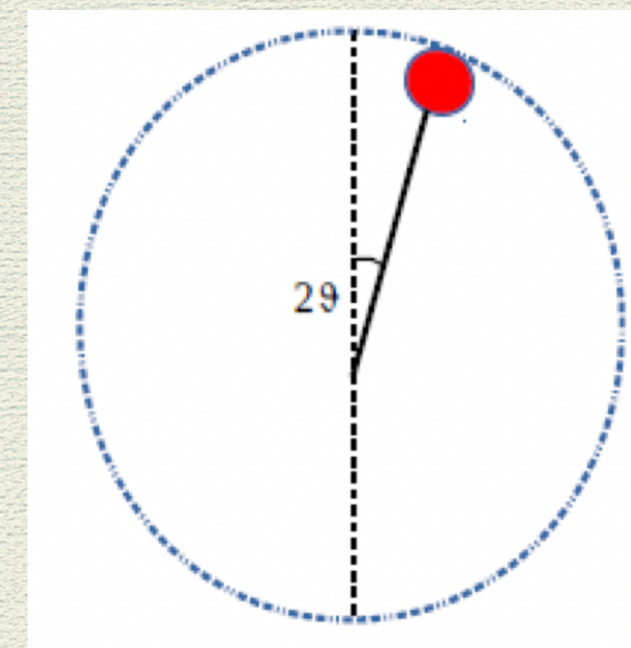
- Can change the n/p ratio through charged current interactions of ν. Relevant for nucleosynthesis.

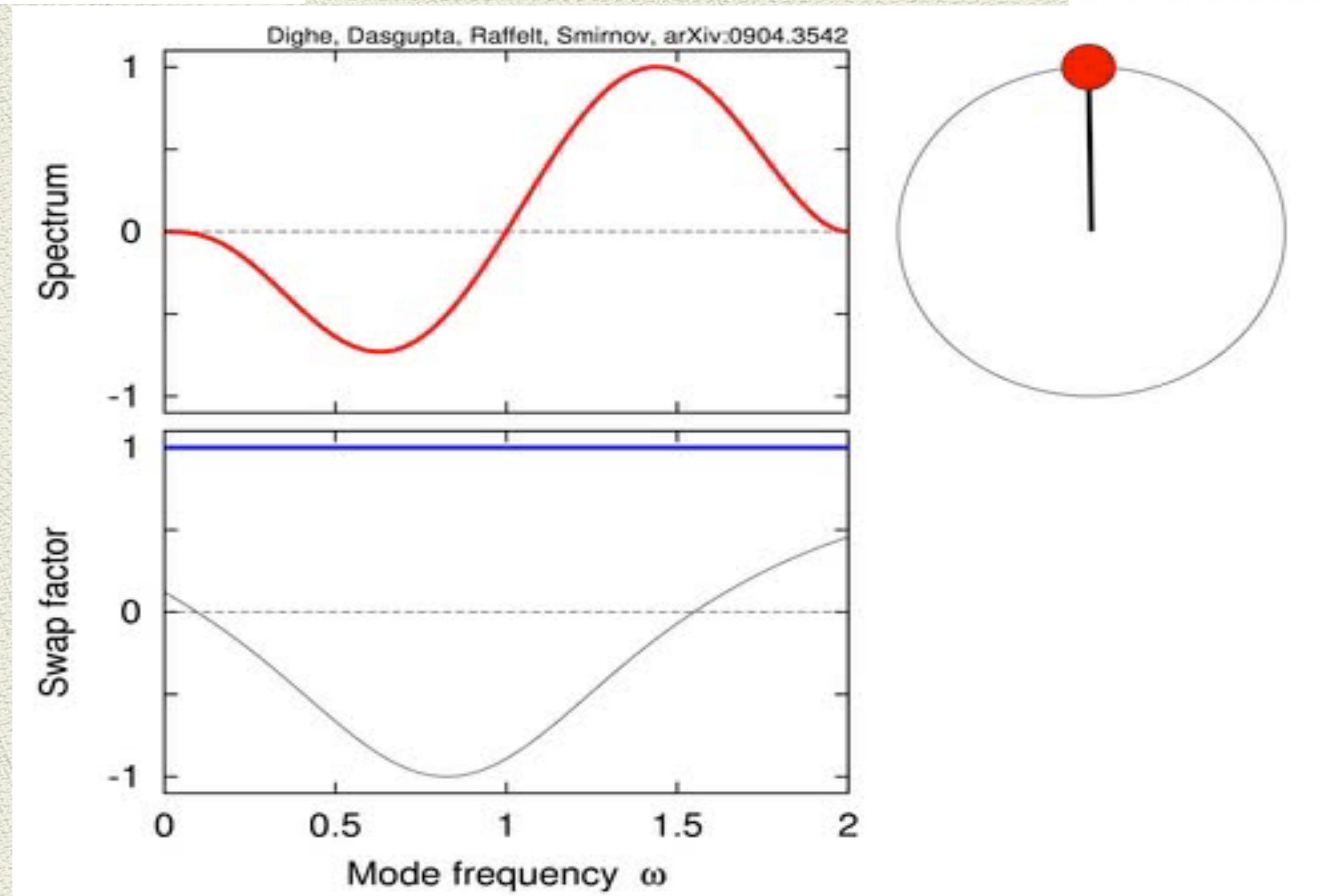
How do we go about this analytically? (1)



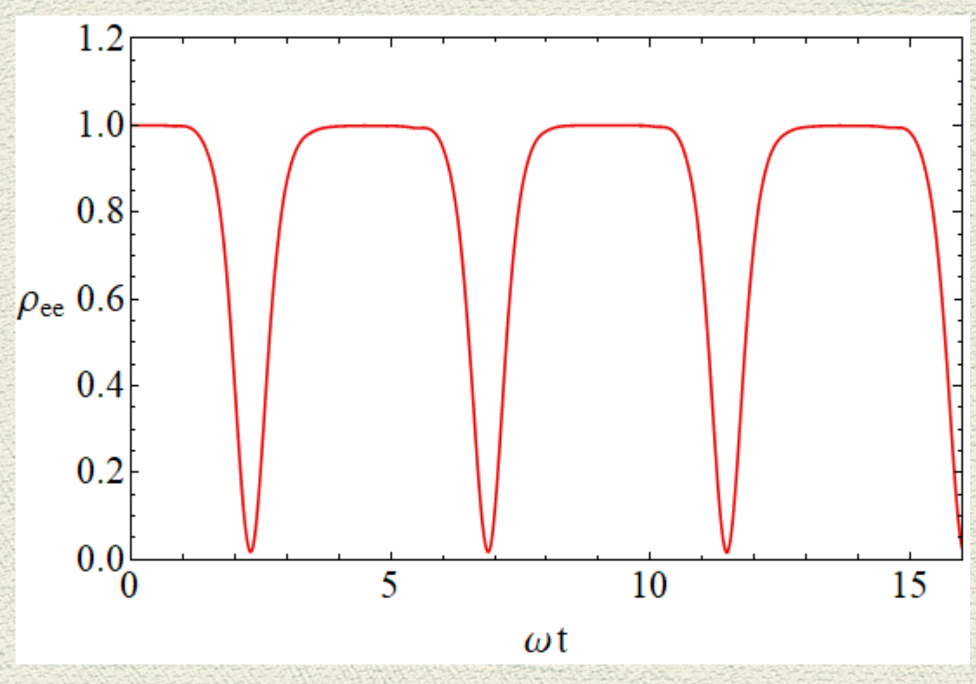
Analytic

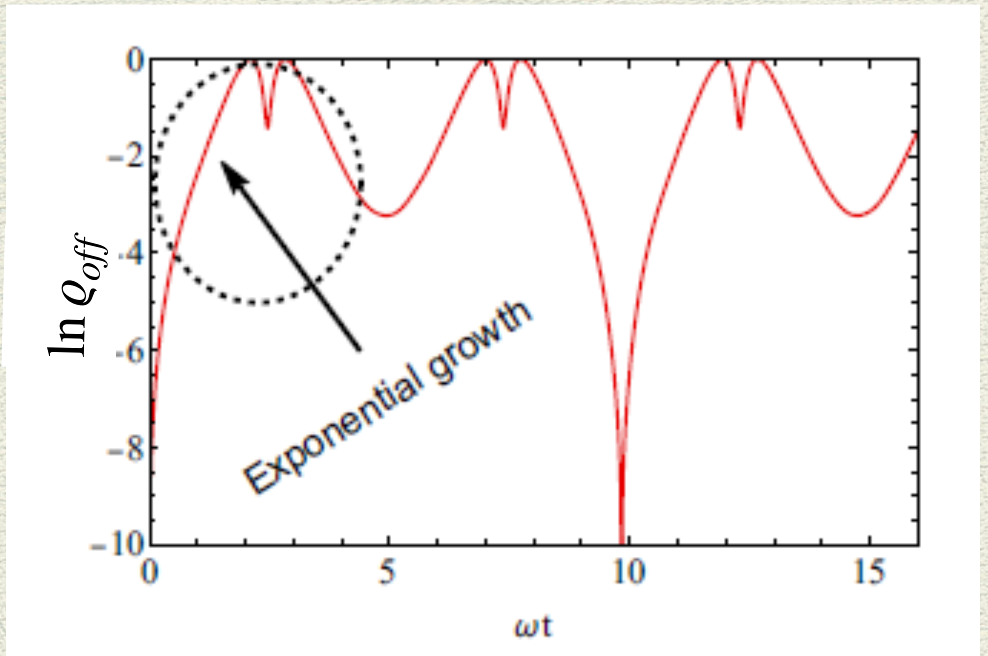
Mapping





How do we go about this analytically? (2)



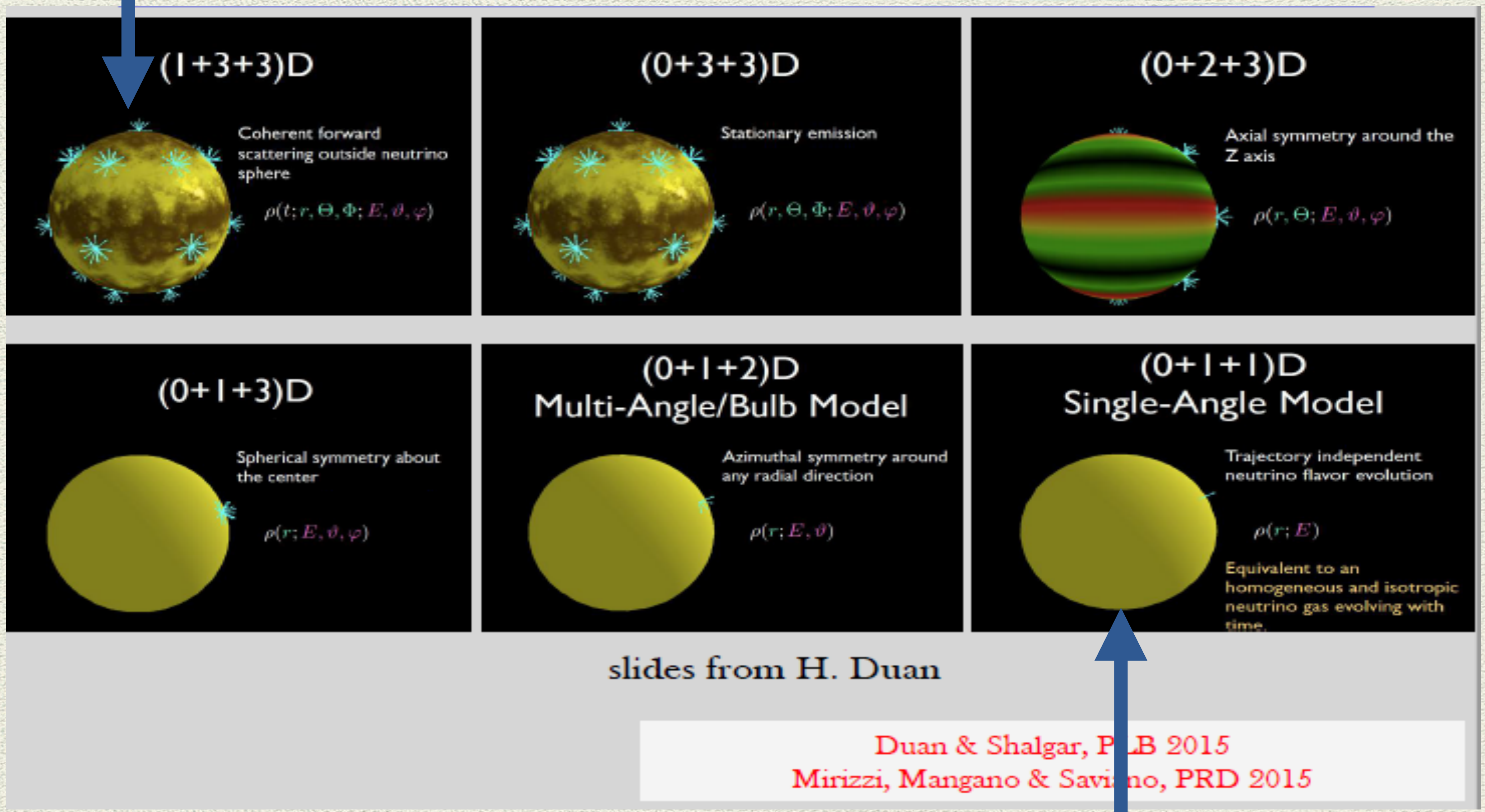


- Interpret flavor oscillations as an instability problem.
- Linearise the Hamiltonian.
  Look for exponential run-away solutions of ϱ_{off} .
- Signals onset of an instability-> growth of coherence among modes.

Banerjee, Dighe and Raffelt, PRD 2011

The pathway

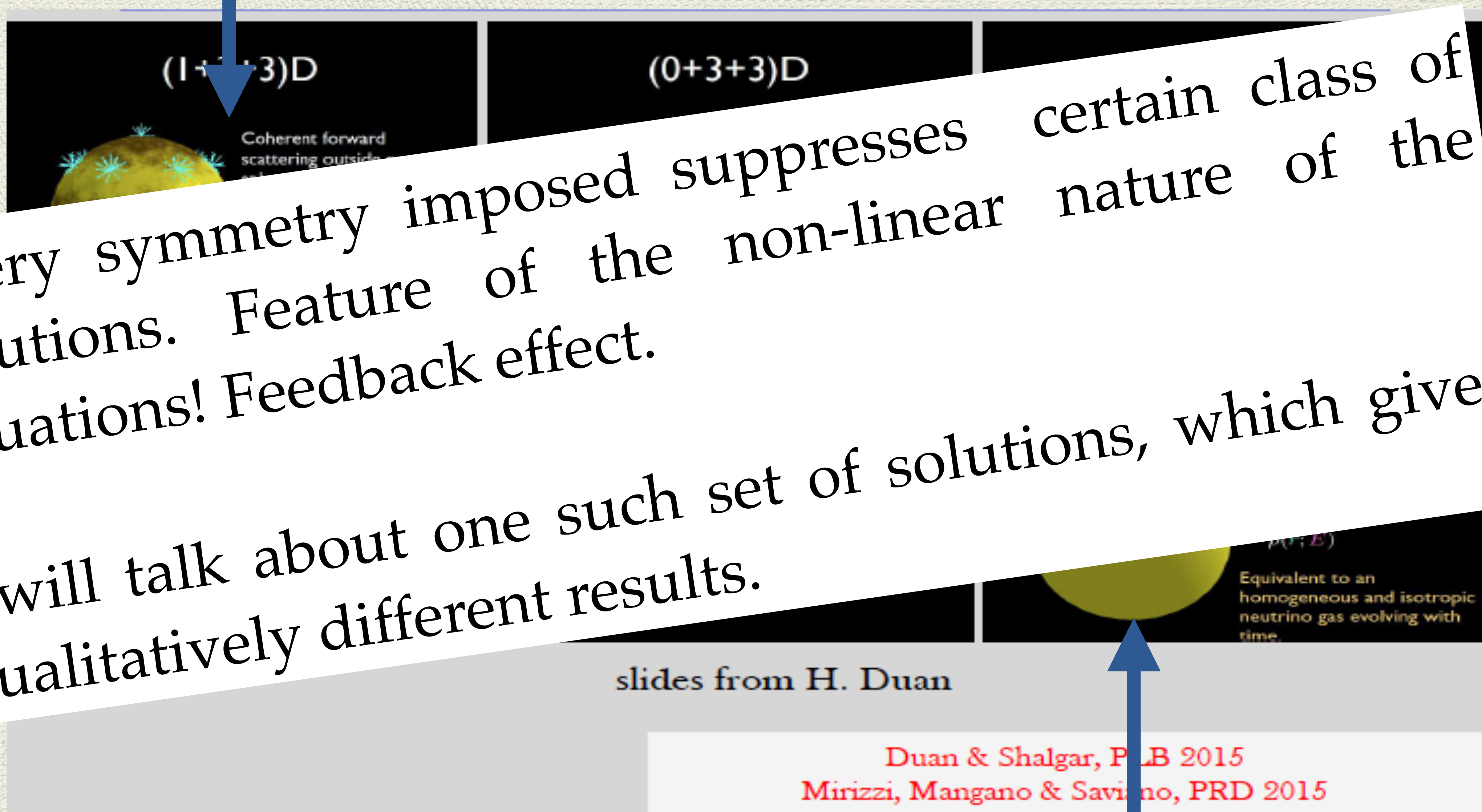
Can do this for few modes



Started here

The pathway

Can do this for few modes

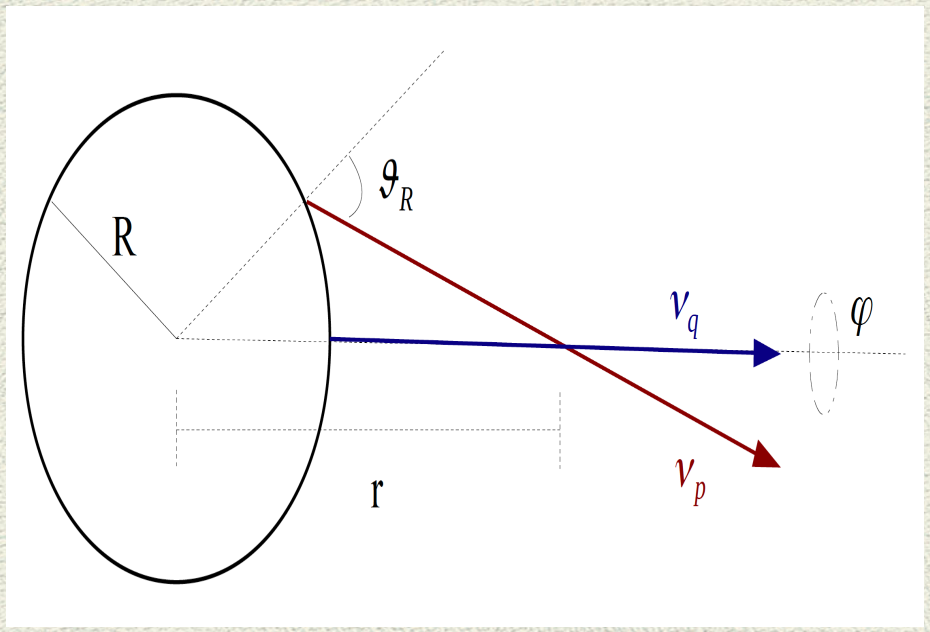


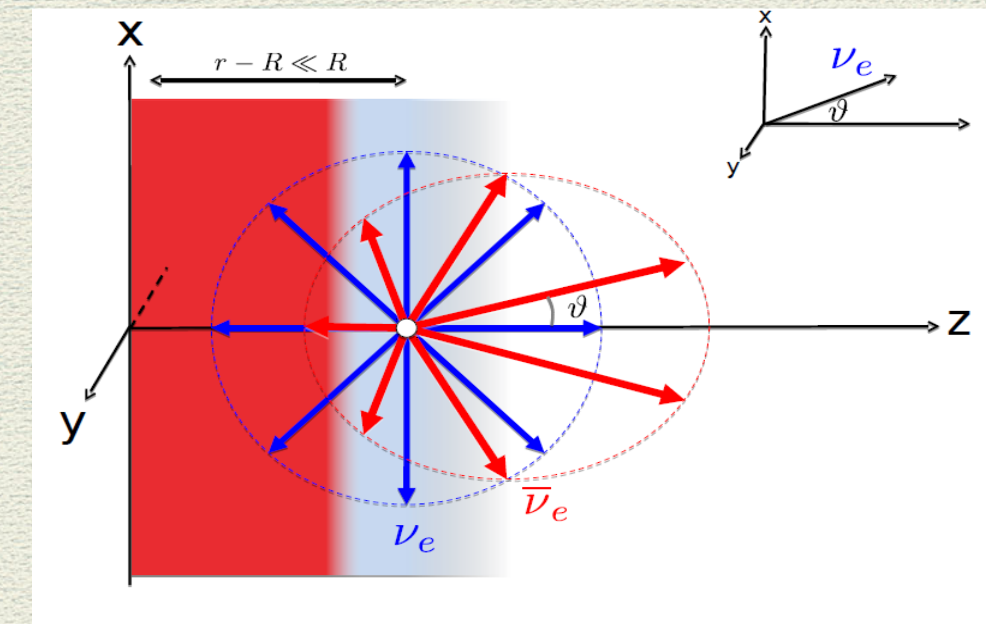
Every symmetry imposed suppresses certain class of solutions. Feature of the non-linear nature of the equations! Feedback effect.

I will talk about one such set of solutions, which gives qualitatively different results.

Started here

Fast flavor oscillations (FFC)



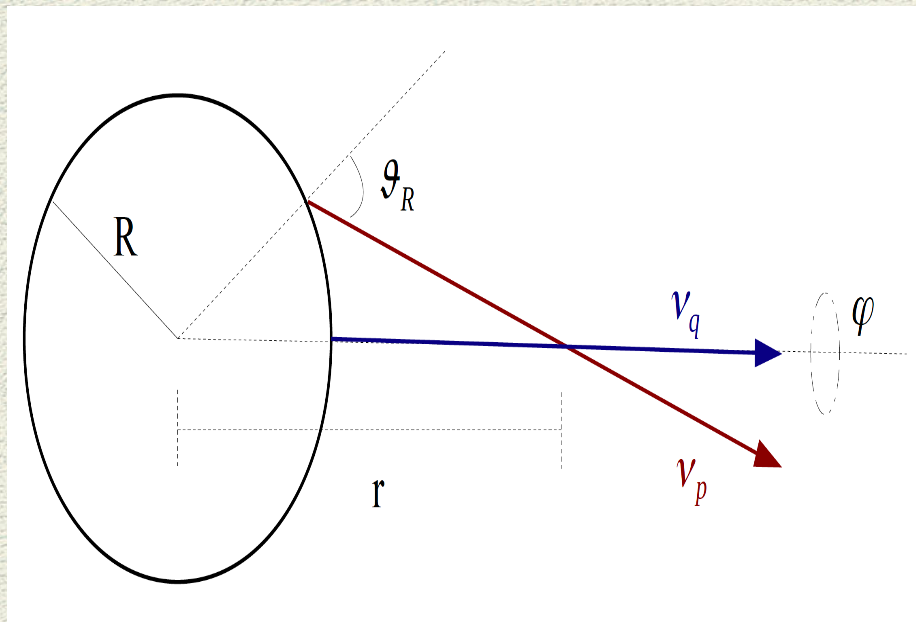


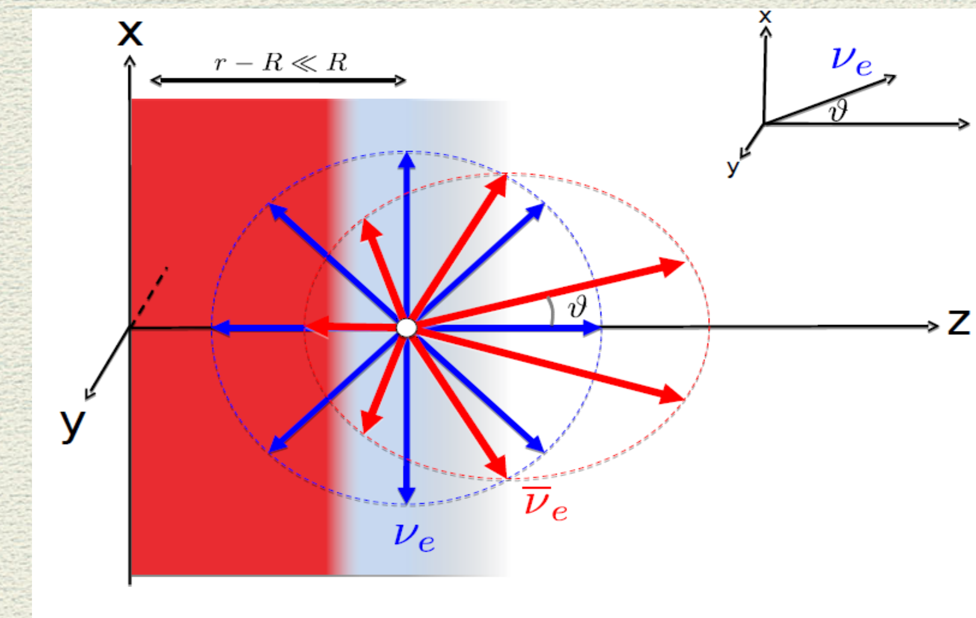
Discard the concept of a distinct neutrino-sphere

Flavor dependent free-streaming. Leads to different angular distributions.

Dasgupta, Mirizzi and MS (JCAP 2017)

Fast flavor oscillations



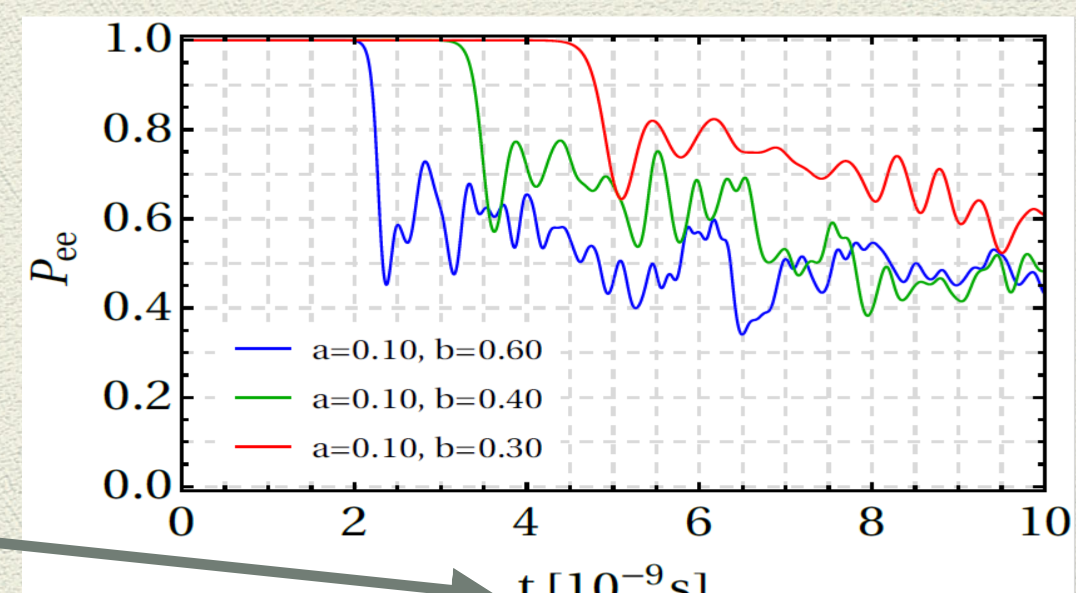


Discard the concept of a distinct neutrino-sphere

Flavor dependent free-streaming. Leads to different angular distributions.

Rapid flavor conversions, rate $\propto n_\nu$

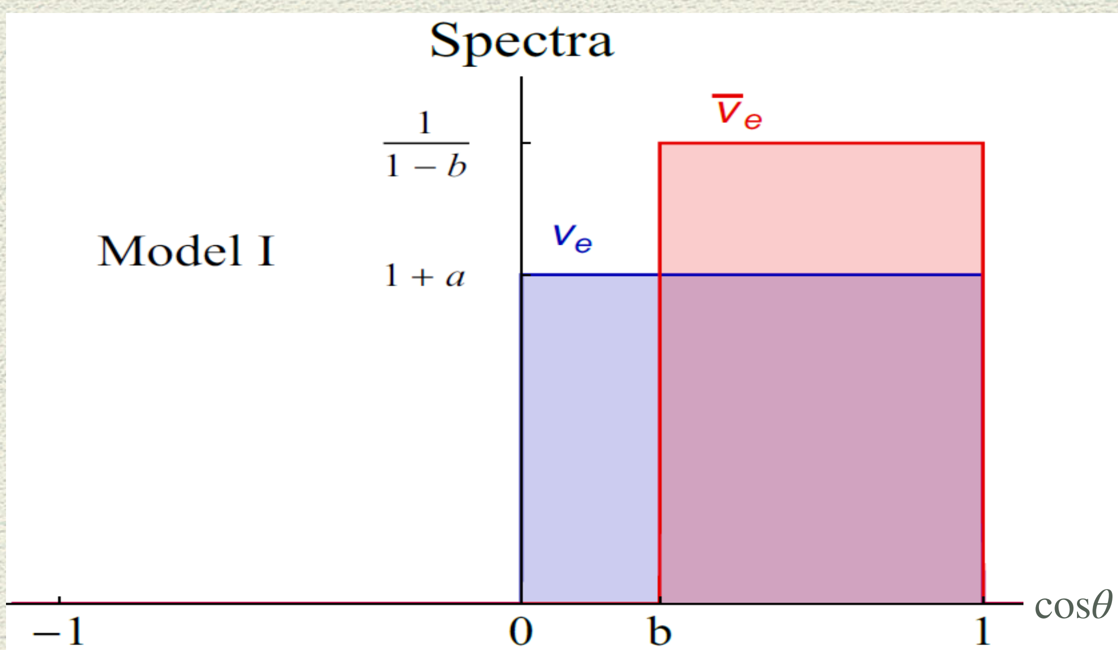
Timescales~ nanoseconds, hence fast conversions!

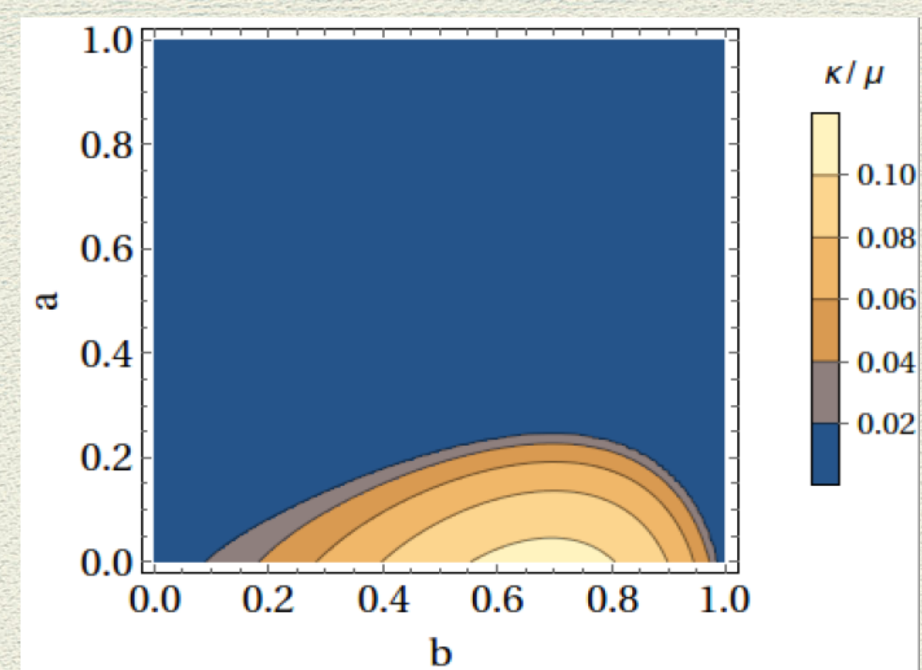


Dasgupta, Mirizzi and MS (JCAP 2017)

Analytical probes

Toy spectra





b = asymmetry in angular emission
$a = n_\nu - \overline{n}_\nu$

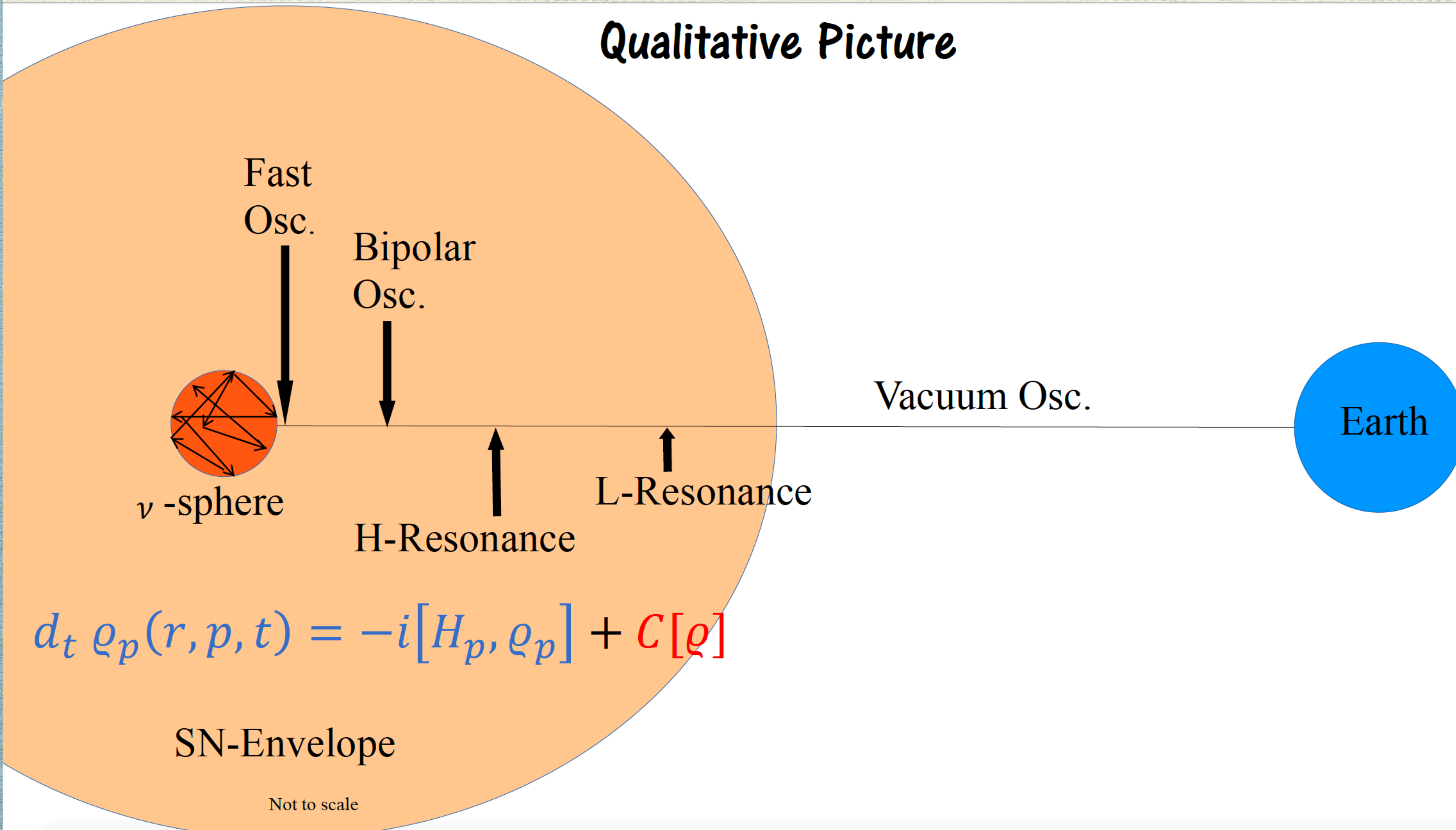
Simple criteria: $b \neq 0$, $a > 0$

1. FFC require a crossing in $h(\theta) = h_{\nu_e}(\theta) - h_{\bar{\nu}_e}(\theta)$.

2. This automatically demands $n_{\bar{\nu}} > n_\nu$ in certain directions of the SN

Dasgupta, Mirizzi and MS (JCAP 2017)

Qualitative Picture



Tip of the iceberg

- FFCs, if present, can change the entire paradigm of SN neutrinos, both simulation as well as theory-wise.

- Leads to almost spectral averaging. All flavor equilibration.

- Relatively new direction, works that I won't talk about here:

1. Collisions and FFC

   - Capozzi, Dasgupta, Mirizzi, MS, Sigl (PRL 2019)

2. Dispersion waves

   Izagguire, Raffelt and Tamborra (PRL 2017)

3. Quartic oscillator.

   -Dasgupta and MS (PRD 2018)

4. An analytic treatment of types of instabilities

   - Dasgupta et al (PRD), Duan et al. (PRD 2019)

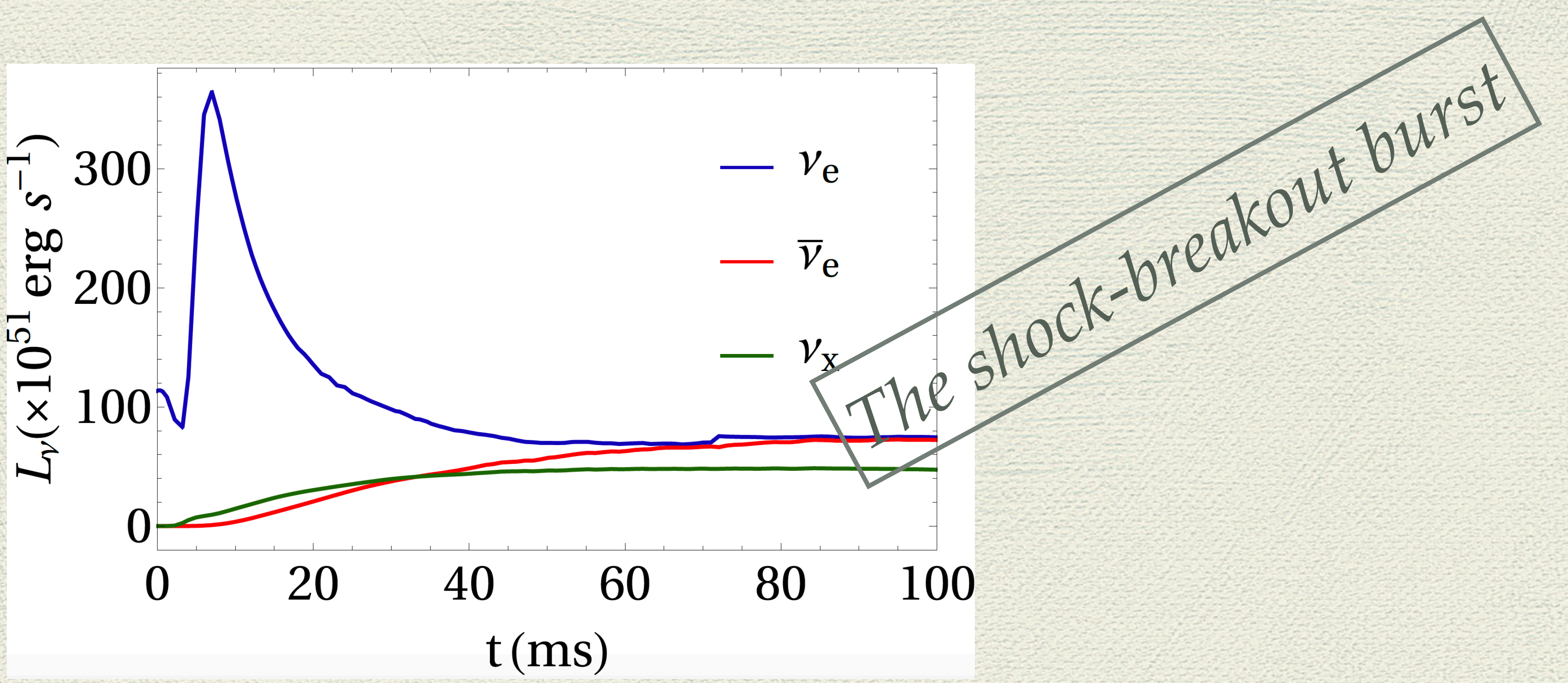
5. Moments of angular distributions

   - Dasgupta, Mirizzi, MS (PRD 2018), Johns, Burrows and Fuller (PRD 2020)

and many more……….

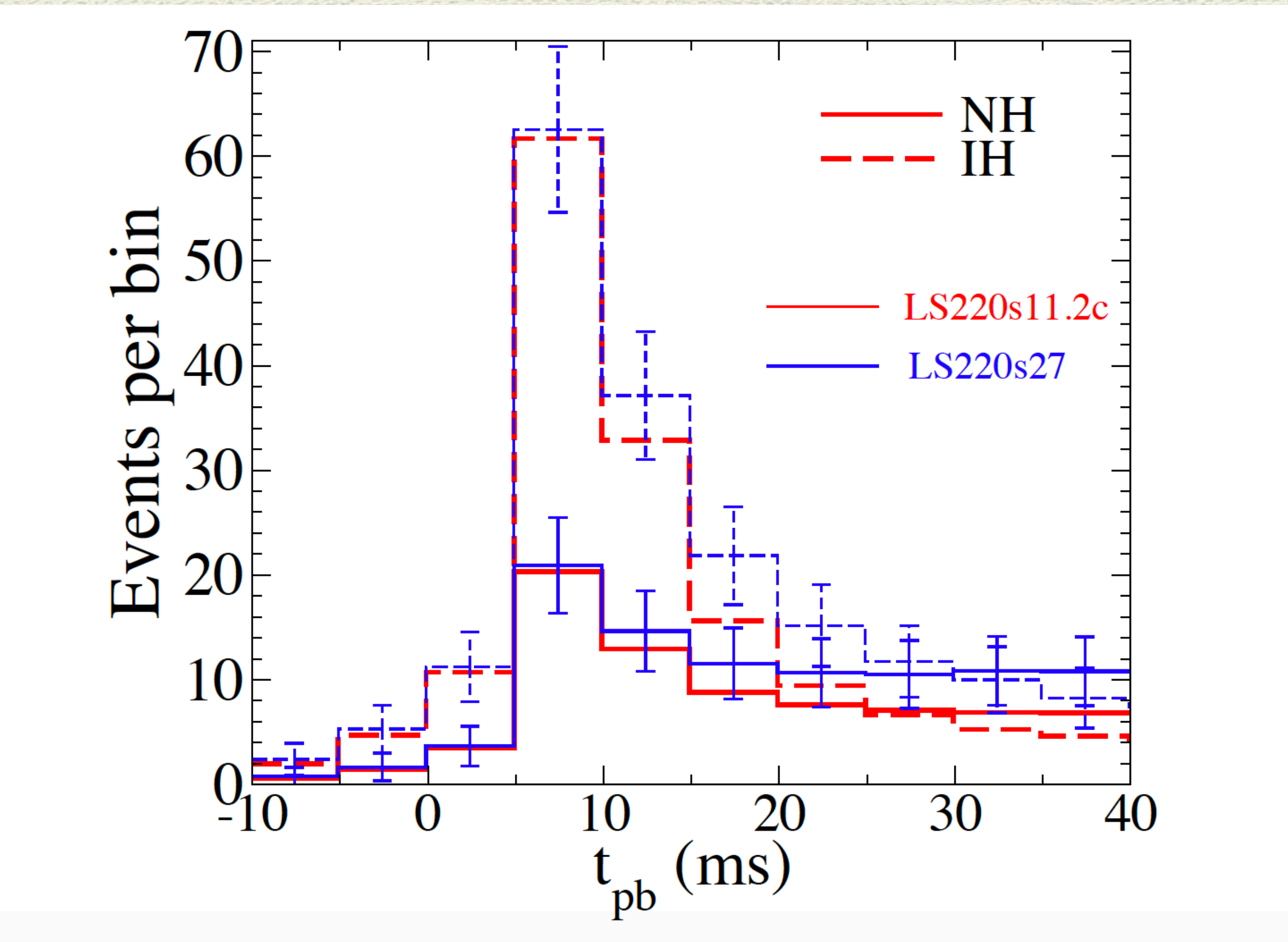
Probe of new physics

A foreward: the neutronization burst



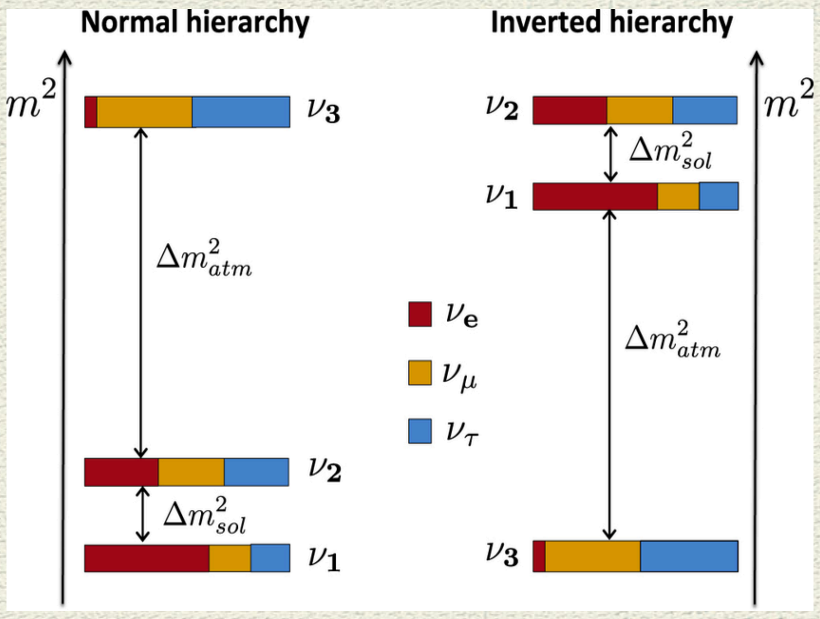
- Large burst of ν_e in the first ~30 ms post bounce.
- Robust feature of all simulations.
- Large ν_e excess, hence no collective oscillations *within the SM.* (Remember $\nu_e\bar{\nu}_e \leftrightarrow \nu_\mu\bar{\nu}_\mu$!)

Sensitivity to mass hierarchy



$$L_{\nu_e}(R_E) \simeq |U_{e2}|^2\, L^0_{\nu_e} = 0.2\, L^0_{\nu_e} \quad \text{IH}$$

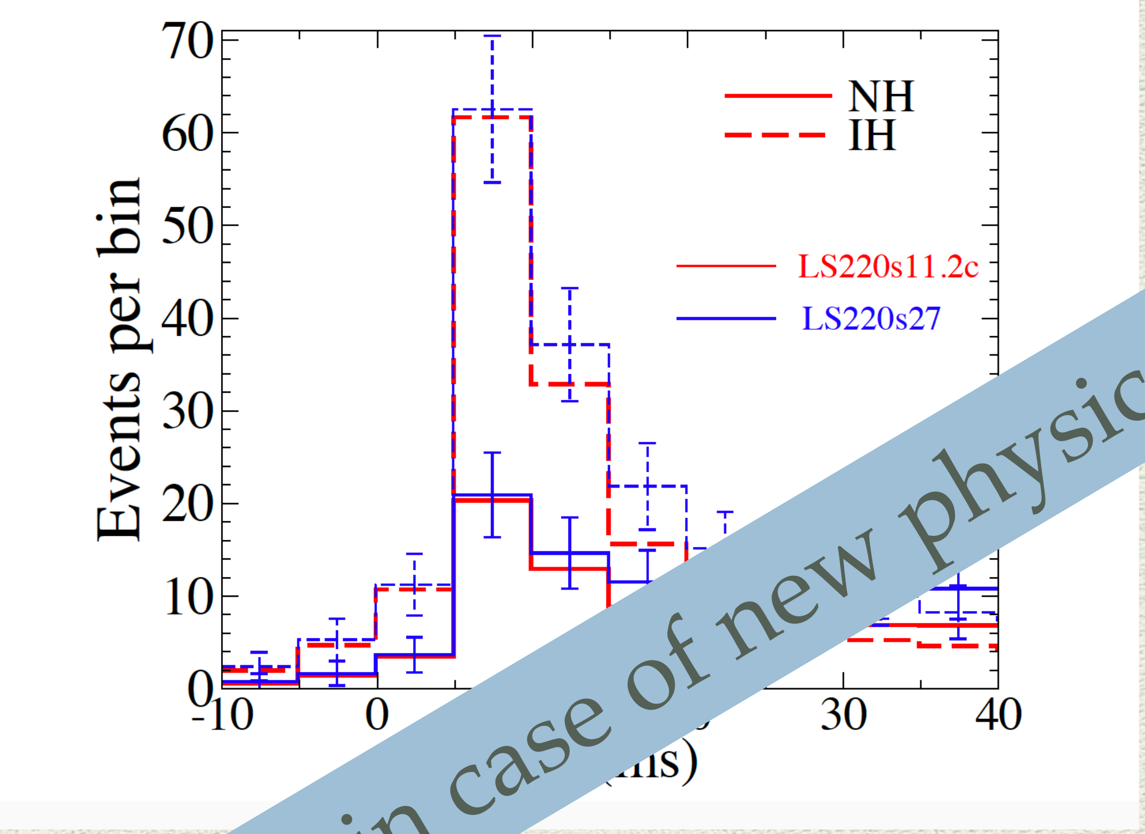
$$L_{\nu_e}(R_E) \simeq |U_{e3}|^2\, L^0_{\nu_e} = 0.03\, L^0_{\nu_e} \quad \text{NH}$$



Independent probe of mass ordering!

Dighe and Smirnov, PRD 2000

Sensitivity to mass hierarchy



What happens in case of new physics?

$|U_{e2}|^2 L^0_{\nu_e} = 0.2\, L^0_{\nu_e}$ IH

$(R_E) \simeq |U_{e3}|^2 L^0_{\nu_e} = 0.03\, L^0_{\nu_e}$ NH

Independent probe of mass ordering!

Neutrino Non-Standard Self-Interactions
NSSI

Based on
1. Dighe, Das and MS (JCAP 1705 (2017) 051)
2. Dighe and MS (PRD97 (2018))

NSSI

- Non-linear EoMs, extremely sensitive to νSI.

$$i\, d_t\, \varrho_p = \left[\sqrt{2} G_F \int d\mathbf{q}\, G\, \varrho_q\, G\,, \varrho_p \right],$$

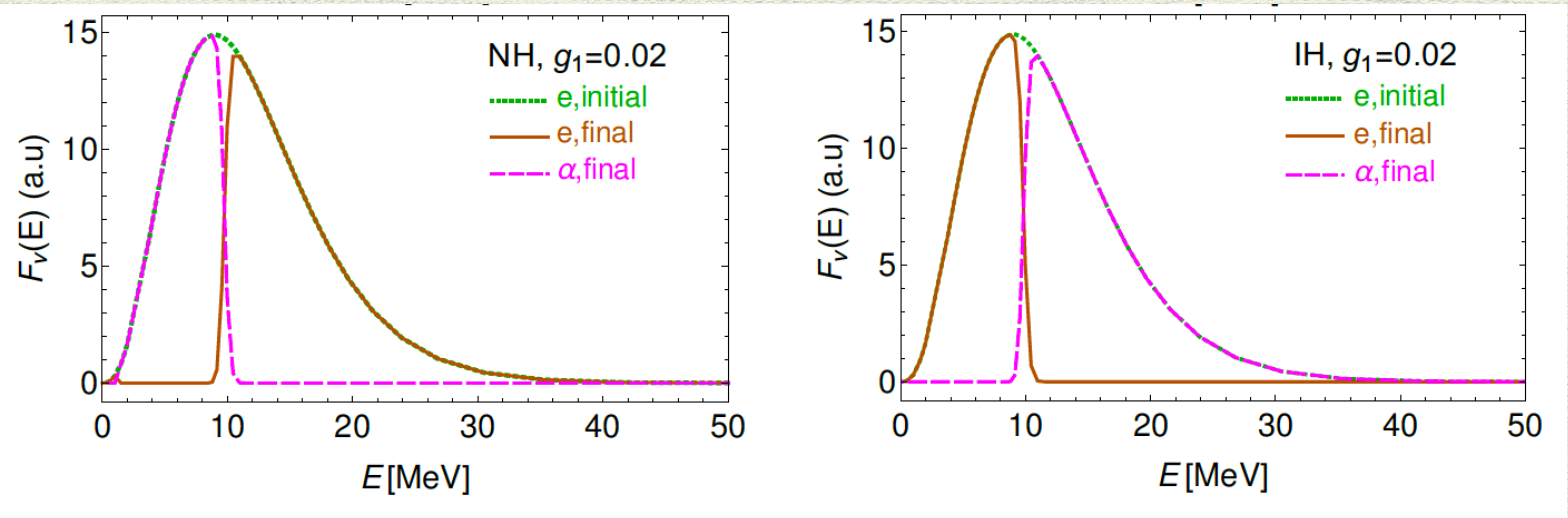
where most generally, $G = \begin{pmatrix} 1 + g_{ee} & g_{ex} \\ g_{ex} & 1 + g_{xx} \end{pmatrix}$.

- $g_{ex} \neq 0$ can populate ν_x from ν_e during neutronization.

- Flavor-violating NSSI can cause coll. osc. now,
  causing distinct spectral splits in neutronization spectra.

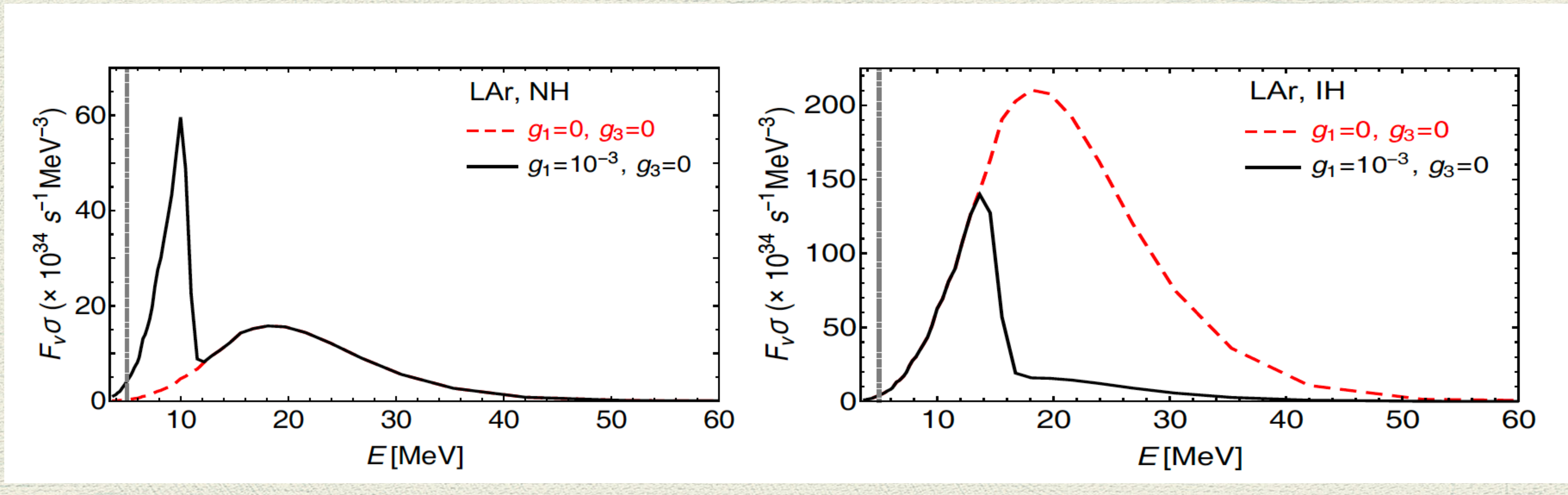
- Effect persists for tiny values of g_{ex} .

NSSI and spectral swaps in neutronization



- A tiny FV-NSSI can trigger splits in ν_e spectra.
- Sensitivity to mass-ordering.
- Can easily be detected by DUNE.

NSSI and spectral swaps in neutronization



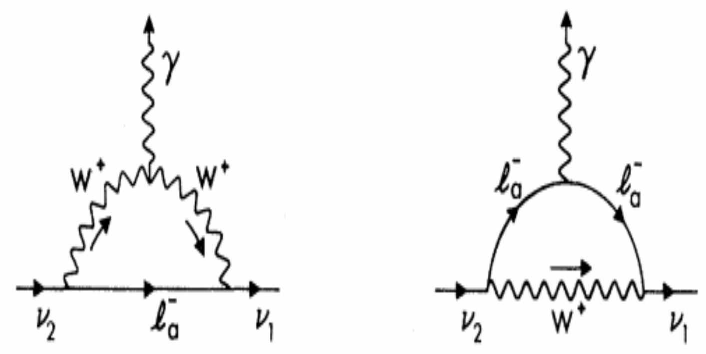
- Distinct splits can be detected at DUNE.
- Put flux dependent constraints on NSSI.
- Caveat: sensitive to details of collective oscillations! Should be explored in more details.

Neutrino Decay

Based on
de Gouvea, Martinez-Soler and MS (PRD101 (2020))

2. Neutrino-decay

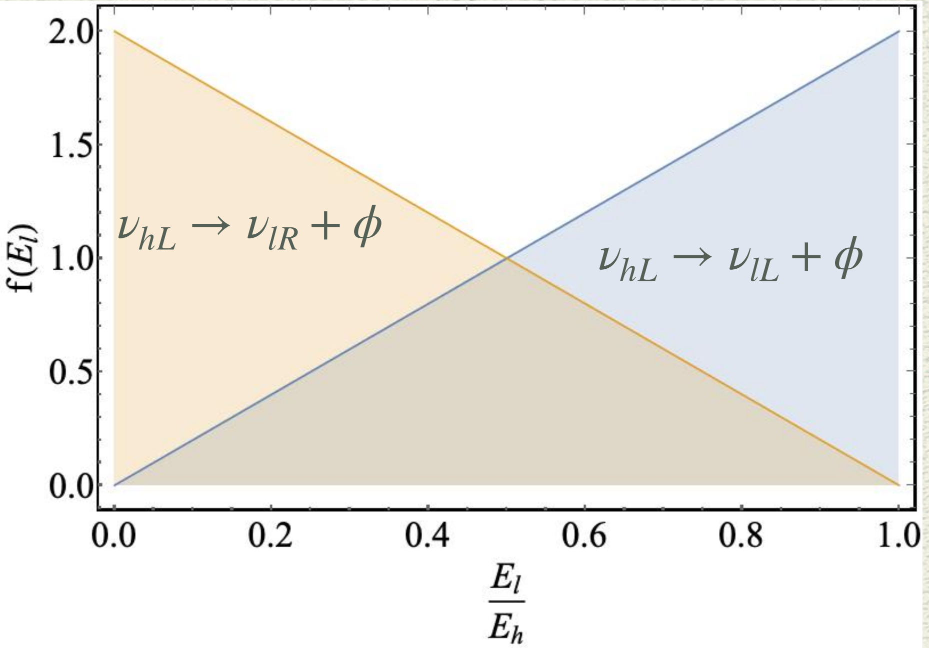
- Massive neutrinos can decay to lighter ones even within the SM. Age longer than universe.



Pal and Wolfenstein (PRD1982)

- New physics can mediate faster decay.

$$\mathscr{L} \supset \nu_h \nu_l^c \phi + \mathrm{H.c.}$$



$\nu_{hL} \to \nu_{lL} + \phi$ .... Helicity cons. (h.c.)

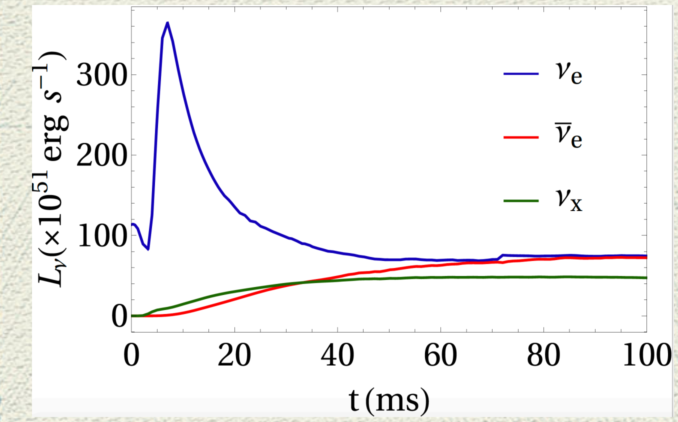
$\nu_{hL} \to \nu_{lR} + \phi$ .... Helicity flip. (h.f.)

Use the ν − burst flux to

(i) Put some of the tightest bound on this decay.

(ii) Distinguish between Dirac and Majorana nature.

How to play this game?



Normal Ordering

NO DECAY

$\nu_h \equiv \nu_3$

$\nu_e \sim 0.02\, \nu_3$

DECAY

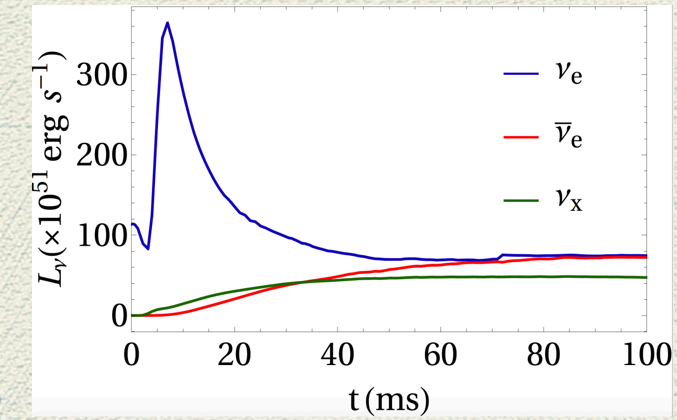
$\nu_l \equiv \nu_1$

$\nu_h \equiv \nu_3$

$\nu_e \sim 0.7\, \nu_e^{\mathrm{in}}$

Enhancement in spectra

How to play this game?



Inverted Ordering

NO DECAY

$\nu_h \equiv \nu_2$

$\nu_e \sim 0.3\,\nu_2$

DECAY

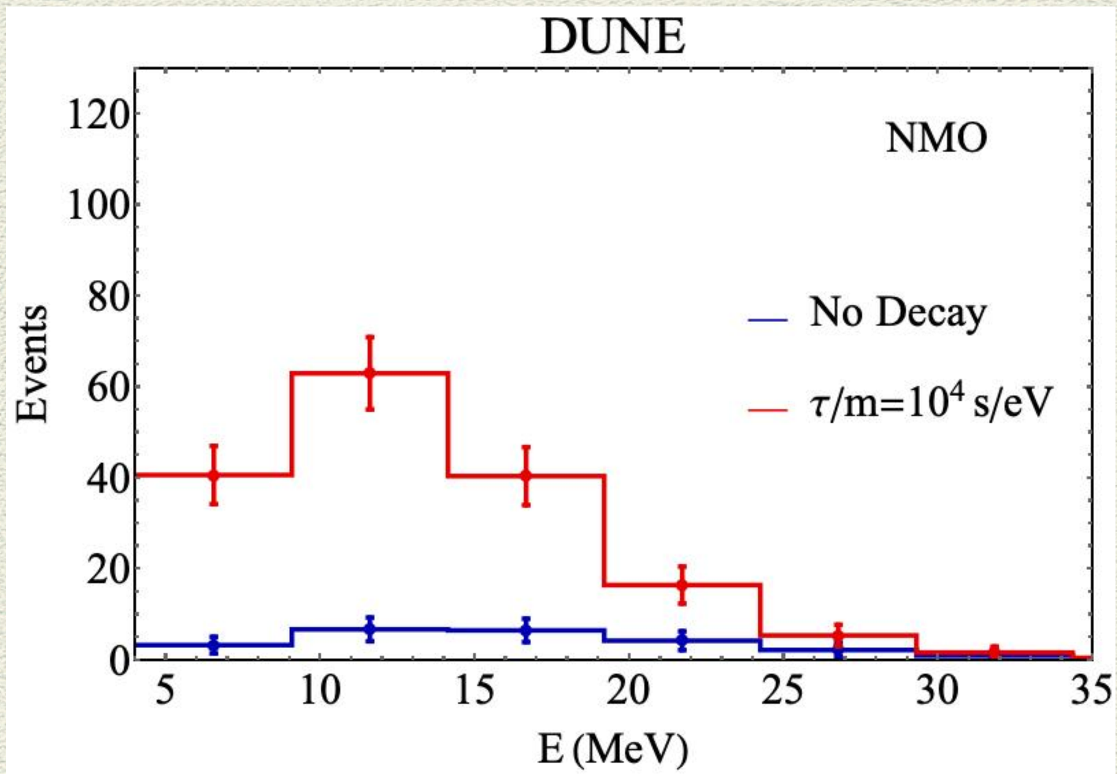
$\nu_l \equiv \nu_3$

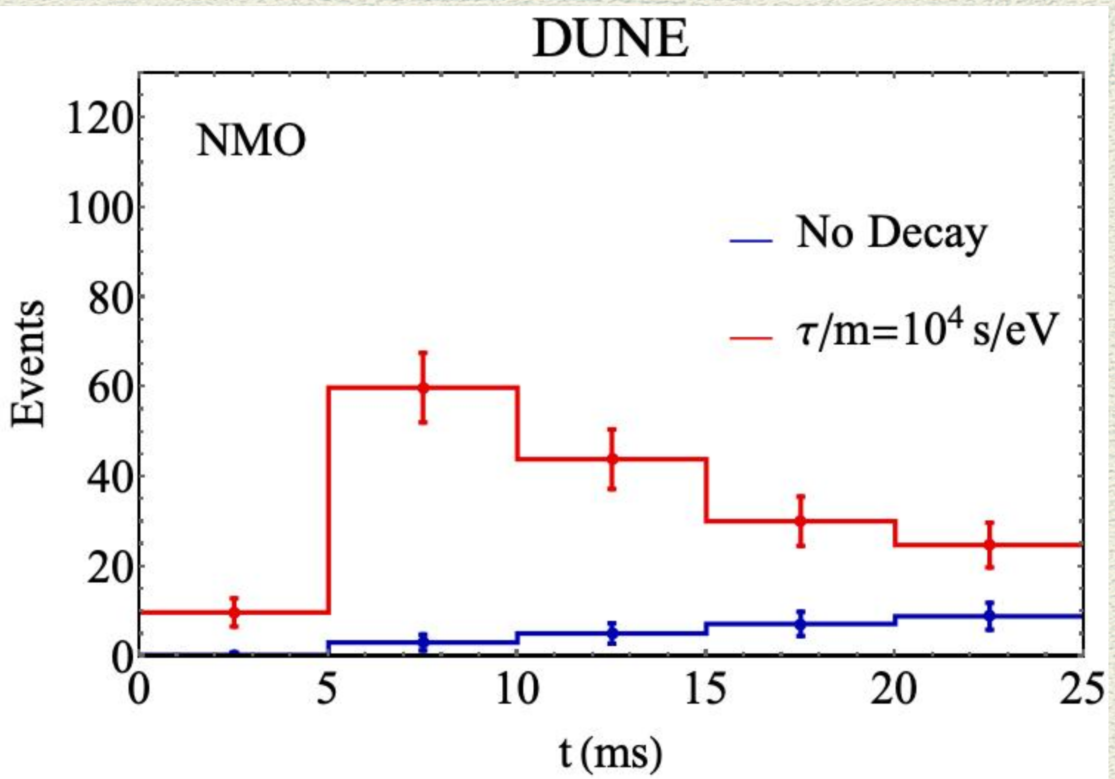
$\nu_h \equiv \nu_2$

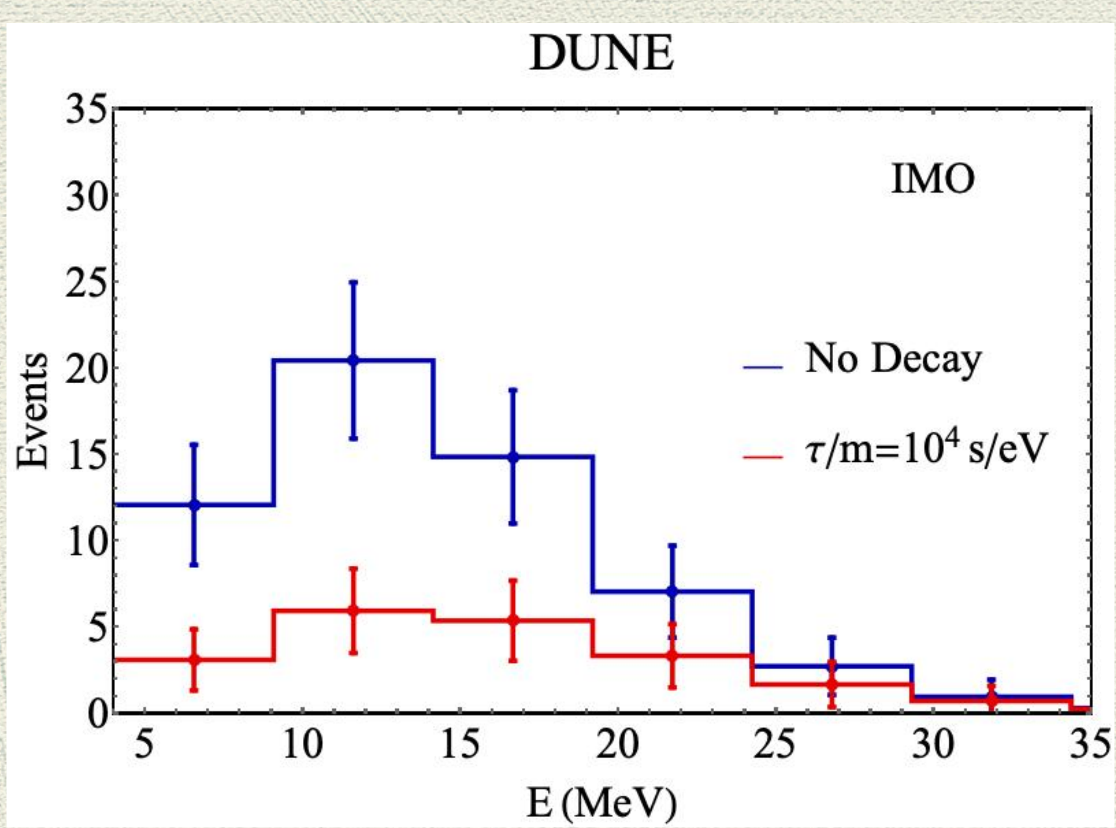
$\nu_e \sim 0.02\,\nu_e^{\mathrm{in}}$

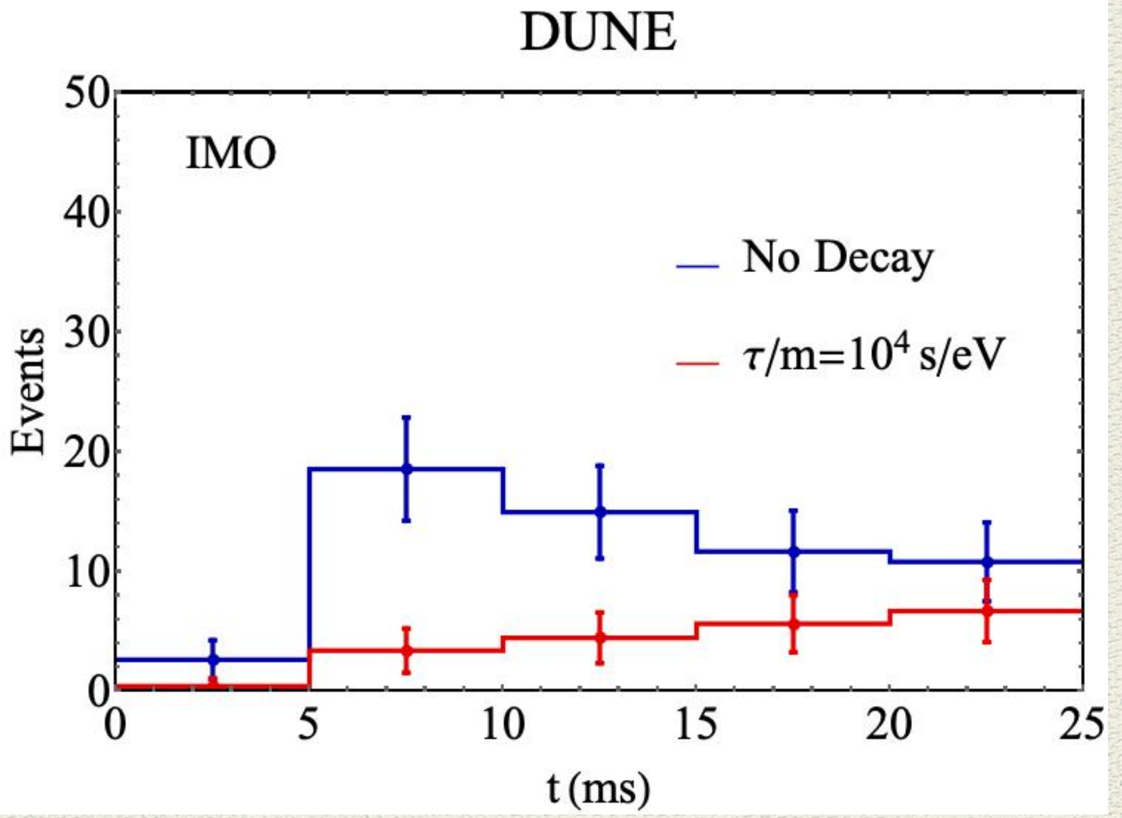
Decline in spectra

Simulate data

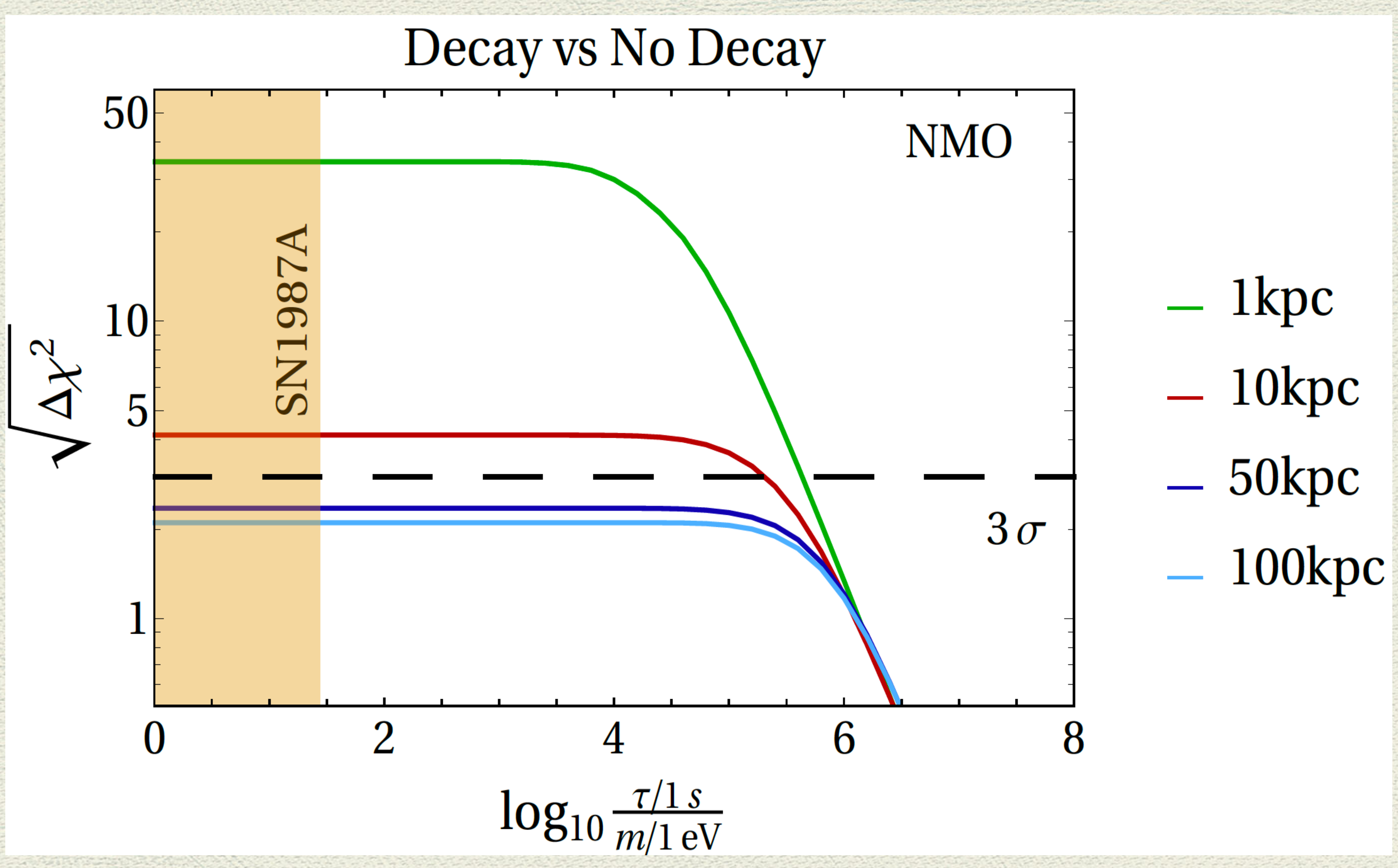








Bounds on neutrino life-time



Experiments sensitive to lifetimes of order of "1 week" for a 1eV mass neutrino

Dirac vs Majorana

$$\mathscr{L}_{\rm Dir} \supset \nu_h \nu_l^c \phi + \mathrm{H.c.}$$

$$\nu_{hL} \to \nu_{lL} + \phi$$

$$\nu_{hL} \to \nu_{lR} + \phi$$

acts as an "inert" neutrino and cannot be observed.

$$\mathscr{L}_{\rm Maj} \supset \nu_h \nu_l \phi + \mathrm{H.c.}$$

$$\nu_{hL} \to \nu_{lL} + \phi$$

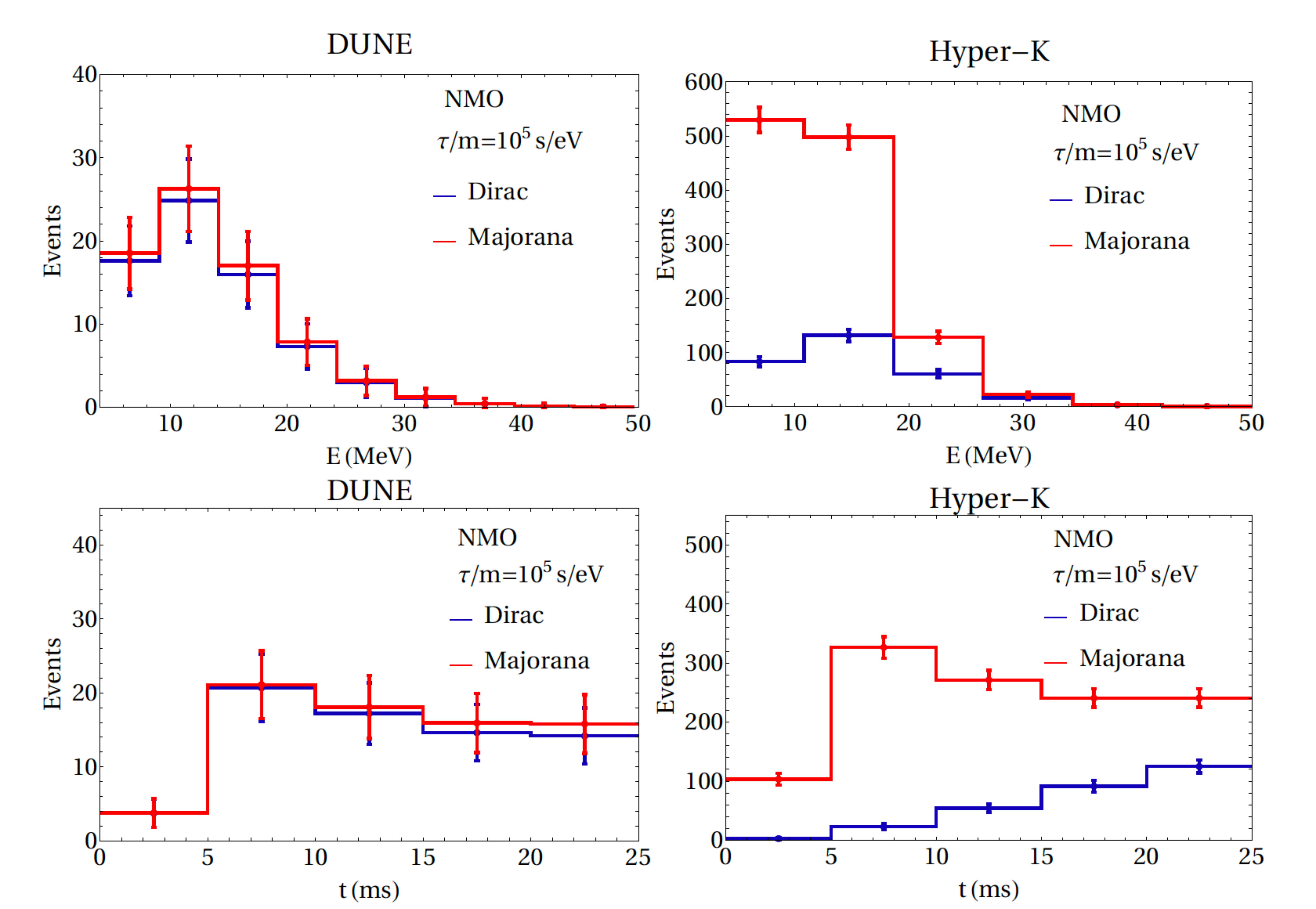
$$\nu_{hL} \to \nu_{lR} + \phi$$

acts as the "antineutrino" - produces an e^+ on interaction—observable

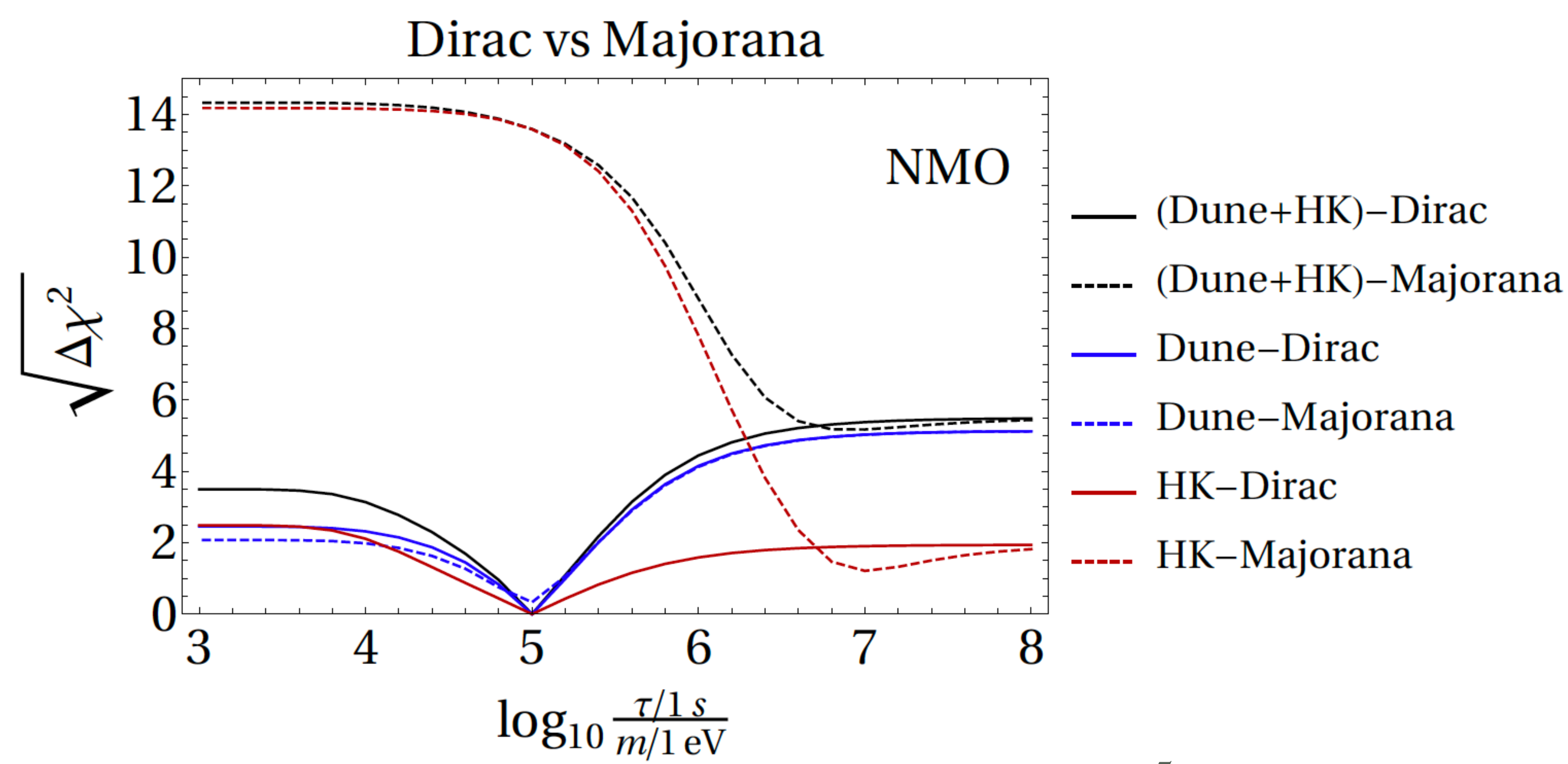
Different signatures in detectors sensitive to ν_e and $\bar{\nu}_e$.

Look at DUNE and HK

Dirac vs Majorana



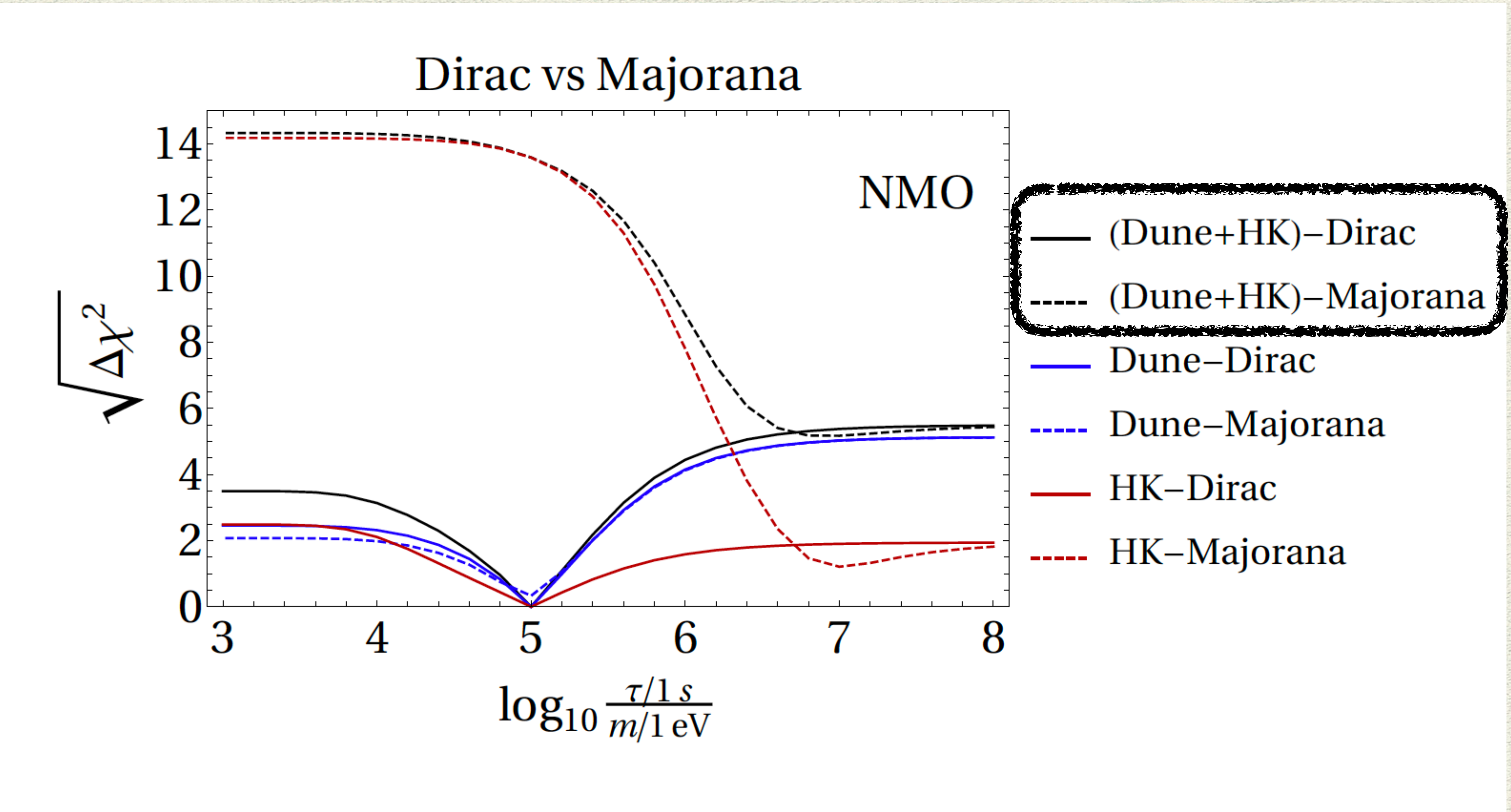
Dirac (D) vs Majorana (M)



Test hypothesis: νs are Dirac, $\tau/m \sim 10^5$s/eV

- DUNE can't distinguish between D and M.
- HK can distinguish as long as $\tau/m \lesssim 10^7\ s/eV$.

Dirac vs Majorana



A combination of DUNE+ HK can distinguish between Dirac and Majorana neutrinos at 5σ.

Conclusion

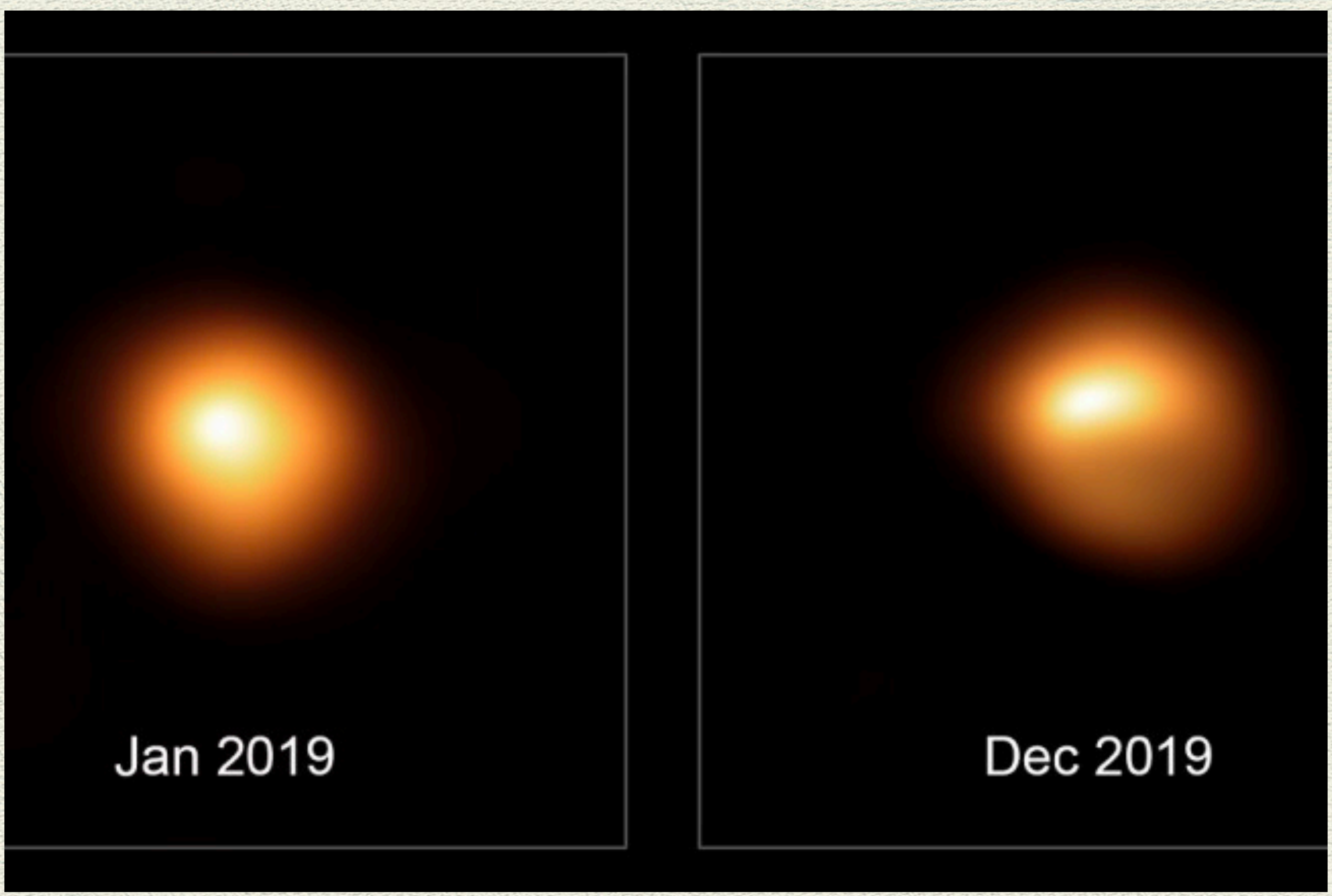
- Core-collapse SNe are one of the very few places where $\nu - \nu$ interactions are relevant. Need better understanding of neutrino flavor propagation in dense media to appreciate its effect.

- Can be used to put some of the best bounds on $\nu - \nu$ non-standard interactions. Non-linear effects amplify tiny effects.

- Naturally long baseline provided can be used to constrain non-standard neutrino decays, and determine the Dirac-Majorana nature.

- Probes of other BSM physics.

Betelgeuse: to catch a dying star!



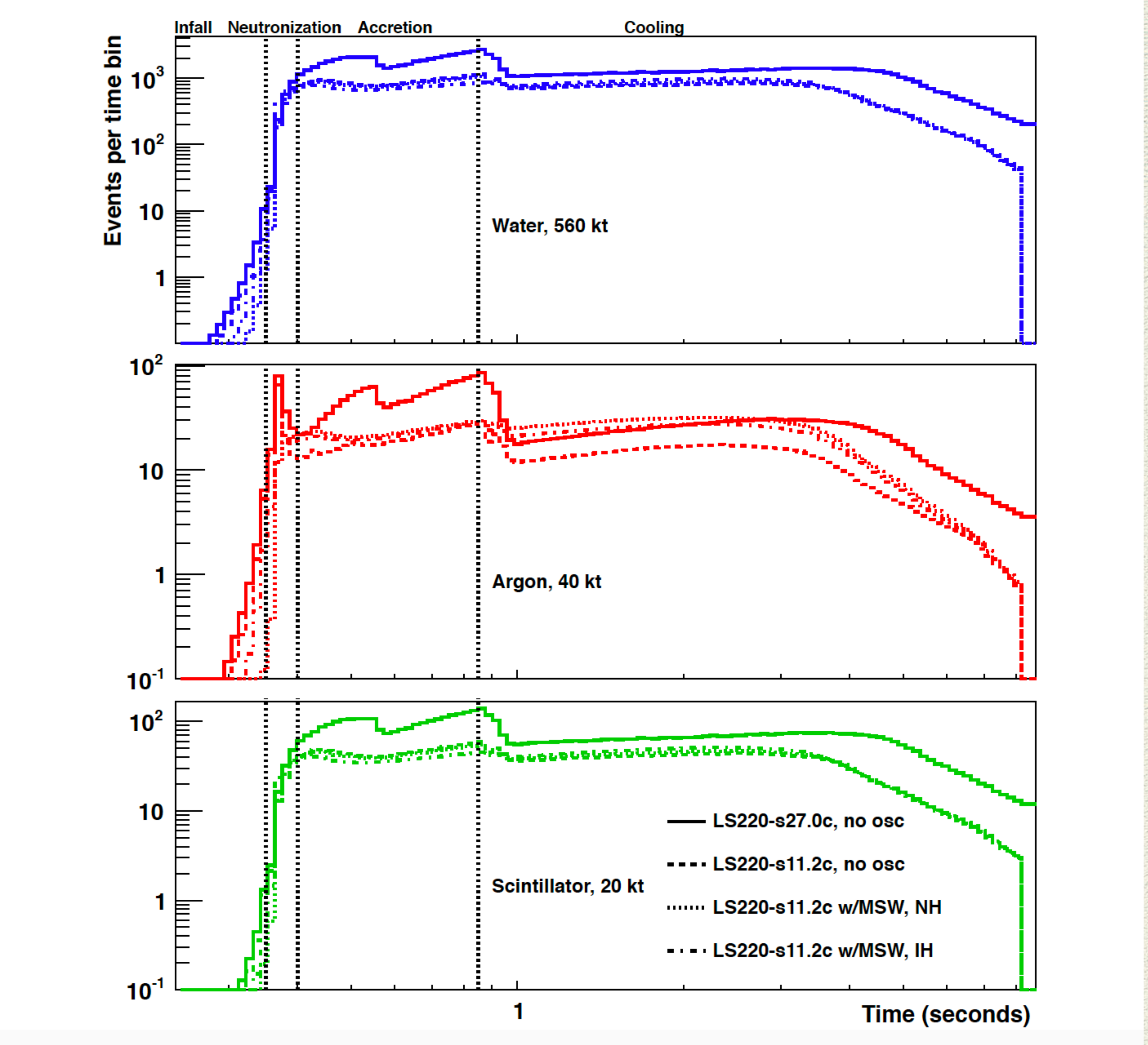
Will Bright Star Betelgeuse Finally Explode? A Look at the Dimming Red Giant in Orion's Shoulder

By Chelsea Gohd January 03, 2020

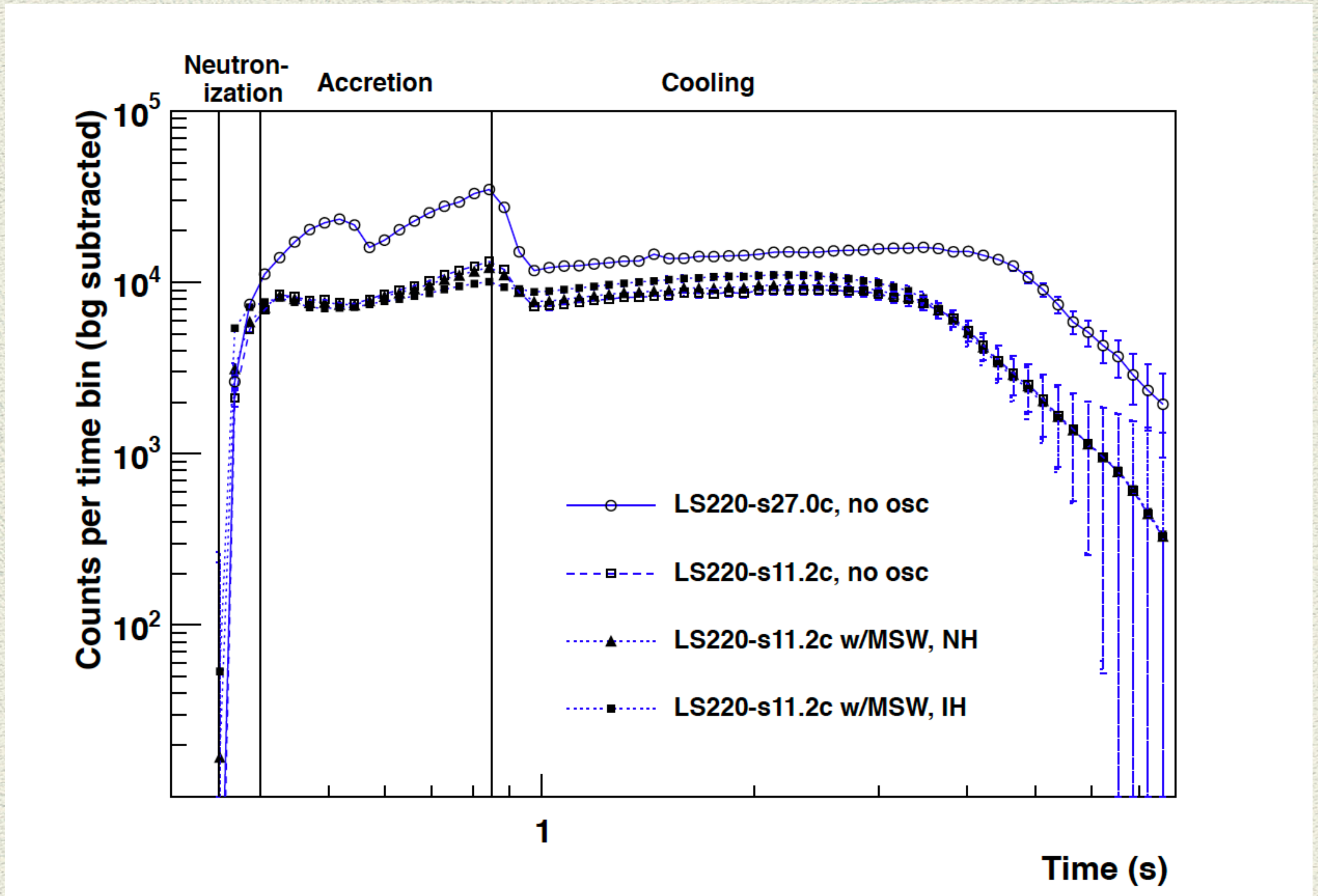
It can't hurt to look up at the night sky just in case.

Thank you!

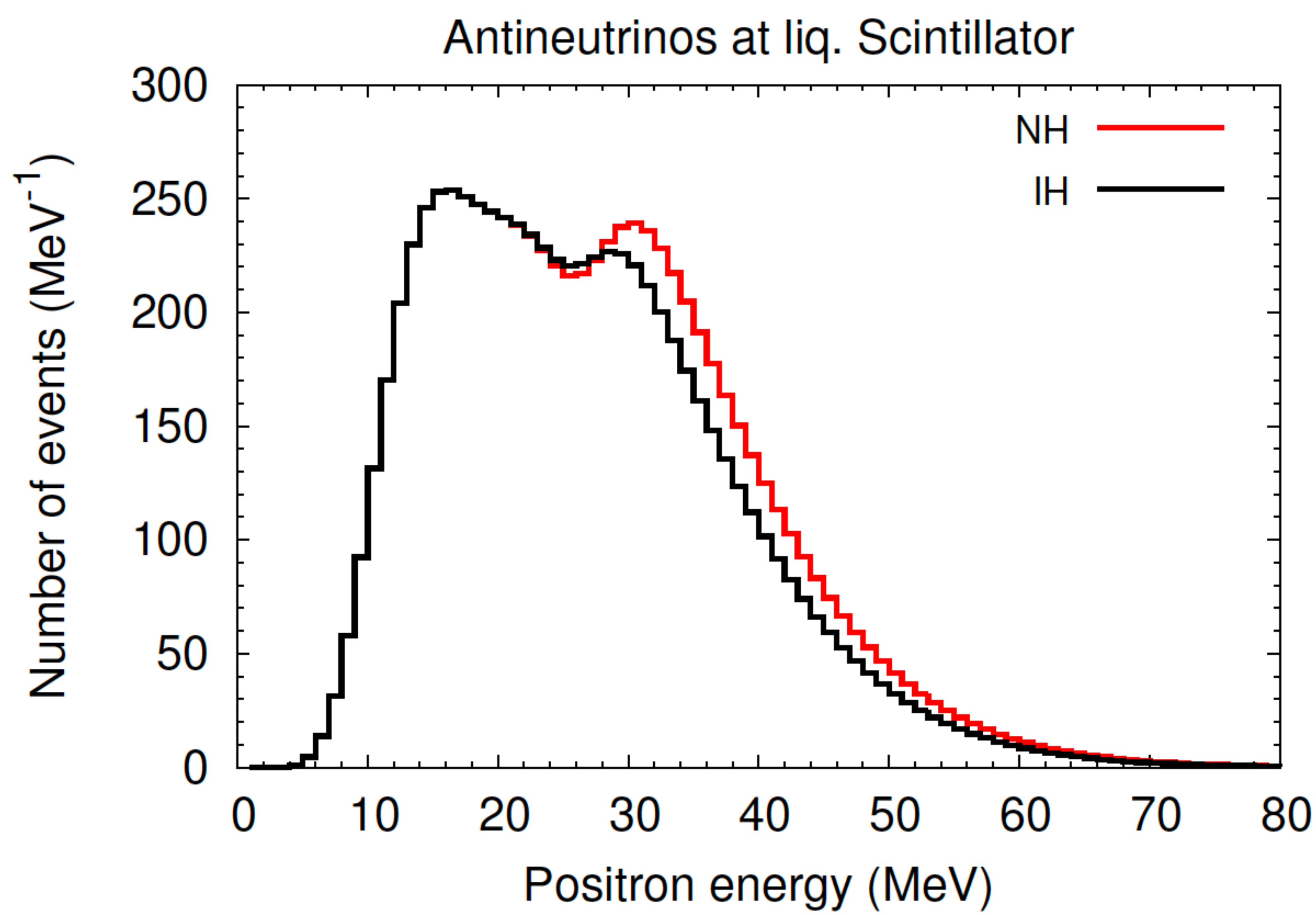
Backup



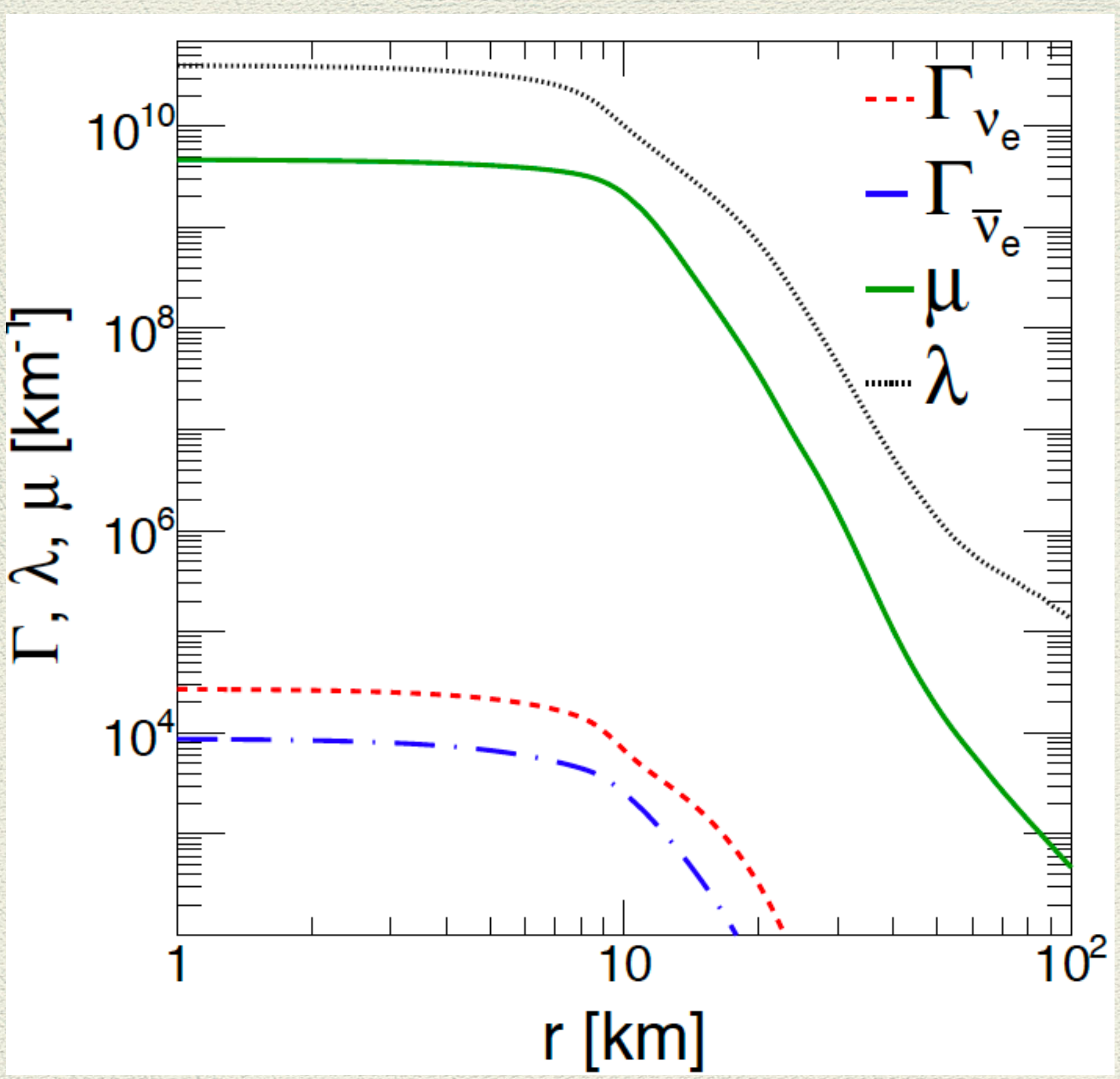
Infall
Neutronization
Accretion
Cooling
Events per time bin
Water, 560 kt
Argon, 40 kt
Scintillator, 20 kt
LS220-s27.0c, no osc
LS220-s11.2c, no osc
LS220-s11.2c w/MSW, NH
LS220-s11.2c w/MSW, IH
Time (seconds)



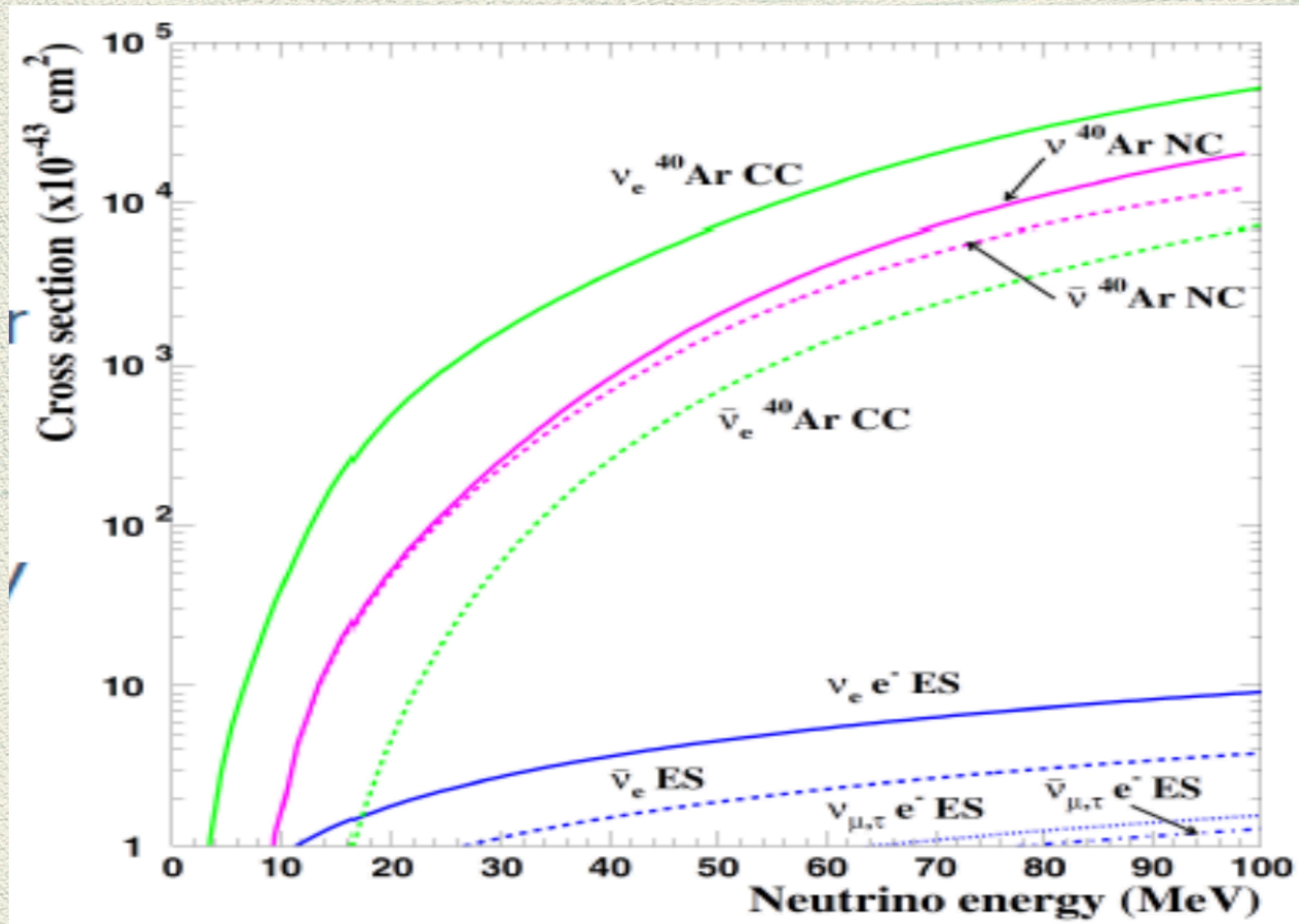
Neutron-
ization
Accretion
Cooling
Counts per time bin (bg subtracted)
10^5
10^4
10^3
10^2
1
Time (s)
LS220-s27.0c, no osc
LS220-s11.2c, no osc
LS220-s11.2c w/MSW, NH
LS220-s11.2c w/MSW, IH



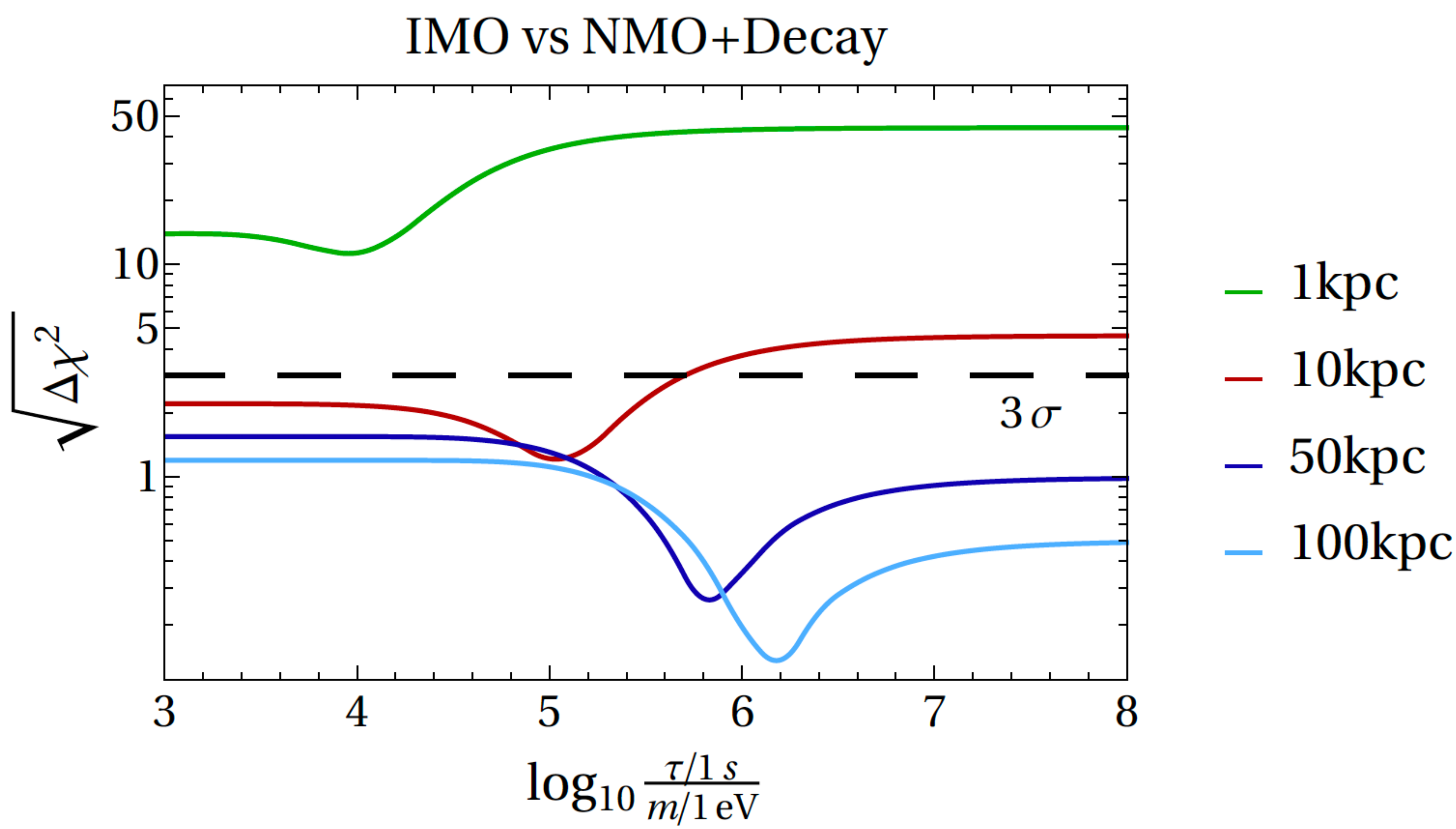
Antineutrinos at liq. Scintillator
Number of events (MeV^{-1})
Positron energy (MeV)
NH
IH
0
50
100
150
200
250
300
0
10
20
30
40
50
60
70
80



Γ, λ, μ [km⁻¹]
10^10
10^8
10^6
10^4
1
10
10^2
r [km]
Γ_νe
Γ_ν̄e
μ
λ



I.Gil-Botella & A.Rubbia, hep-ph/0307222, JCAP 10 (2003) 009, JCAP 08 (2004) 001



IMO vs NMO+Decay
50
10
5
1
$\sqrt{\Delta\chi^2}$
$3\,\sigma$
3
4
5
6
7
8
$\log_{10}\frac{\tau/1\,s}{m/1\,\mathrm{eV}}$
1kpc
10kpc
50kpc
100kpc

Detector	Type	Mass (kt)	Location	Events	Flavors	Status
Super-Kamiokande	H_2O	32	Japan	7,000	$\bar{\nu}_e$	Running
LVD	C_nH_{2n}	1	Italy	300	$\bar{\nu}_e$	Running
KamLAND	C_nH_{2n}	1	Japan	300	$\bar{\nu}_e$	Running
Borexino	C_nH_{2n}	0.3	Italy	100	$\bar{\nu}_e$	Running
IceCube	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Running
Baksan	C_nH_{2n}	0.33	Russia	50	$\bar{\nu}_e$	Running
MiniBooNE*	C_nH_{2n}	0.7	USA	200	$\bar{\nu}_e$	(Running)
HALO	Pb	0.08	Canada	30	ν_e, ν_x	Running
Daya Bay	C_nH_{2n}	0.33	China	100	$\bar{\nu}_e$	Running
NOνA*	C_nH_{2n}	15	USA	4,000	$\bar{\nu}_e$	Turning on
SNO+	C_nH_{2n}	0.8	Canada	300	$\bar{\nu}_e$	Near future
MicroBooNE*	Ar	0.17	USA	17	ν_e	Near future
DUNE	Ar	34	USA	3,000	ν_e	Proposed
Hyper-Kamiokande	H_2O	560	Japan	110,000	$\bar{\nu}_e$	Proposed
JUNO	C_nH_{2n}	20	China	6000	$\bar{\nu}_e$	Proposed
RENO-50	C_nH_{2n}	18	Korea	5400	$\bar{\nu}_e$	Proposed
LENA	C_nH_{2n}	50	Europe	15,000	$\bar{\nu}_e$	Proposed
PINGU	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Proposed